URBAN HEAT ISLAND MITIGATION POTENTIAL OF GREEN INFRASTRUCTURE: INSIGHTS FROM LST, LULC, AND ENVI-MET MODELING IN PAŞAALANI NEIGHBORHOOD, BALIKESIR, TÜRKIYE

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Abstract. This study investigates green infrastructure strategies to mitigate urban heat island effects in the Paşaalanı neighbourhood of Balıkesir, Türkiye. The research was structured in three stages. First, neighbourhood-scale land use/land cover (LULC) changes were analysed for 2000, 2013, and 2024. Second, land surface temperature (LST) patterns for the same years were evaluated to assess the thermal consequences of urban transformation. The results revealed a substantial increase in built-up areas, a marked decline in vegetation cover, and an expansion of high-temperature zones, with LST values ranging from 33.20 to 40.31 °C. Third, ENVI-met simulations were conducted in a selected sub-area under three scenarios: baseline, deciduous vegetation, and coniferous vegetation. While thermal differences were limited at 07:00, more pronounced variations emerged later in the day. At 10:00, the baseline scenario showed localised heat accumulation over impervious surfaces, whereas deciduous vegetation generated broader cooling zones. At 13:00, the deciduous scenario recorded the lowest minimum potential air temperature (28.70 °C), while the coniferous scenario exhibited a wider extent of temperatures above 31.52 °C. By 16:00, deciduous vegetation maintained the strongest cooling effect, producing a more thermally balanced microclimate. These findings highlight green infrastructure as a critical strategy for enhancing urban thermal resilience and sustainability.
Keywords: *landscape planning, urban heat island (UHI), land surface temperature (LST), blue-green infrastructure, ENVI-met, ecology, sustainability and energy-efficient design in architecture*

Introduction

Increasing population pressure accelerates urban development activities aimed at meeting essential needs such as housing, transportation, and other fundamental services (Sun et al., 2024; Ogunbode et al., 2025). Not only population growth but also the broader processes of globalization have accelerated the spatial expansion of urban areas, leading to a continual increase in the built environment. This transformation is reshaping the physical morphology of cities, whilst also having a significant impact on changes in land use and land cover (LULC), as well as environmental sustainability (Lambin et al., 2001; Şenik and Uzun, 2022; Hua et al., 2024). This process is leading to significant changes in land-use patterns, particularly in regions experiencing rapid urbanization, and is reshaping the spatial organization. The changes that have occurred over time have created significant pressures on the urban ecosystem. This has resulted in an increase in building density and the proliferation of impervious hard surfaces, while concomitantly leading to a decrease in green spaces (Ahiablame et al., 2012; Liu et al., 2017; Kim et al., 2024; Hepcan et al., 2025). In addition, the increase in building density and population is resulting in a substantial rise in the city's total energy demand. The reliance on non-renewable energy sources for meeting energy demand leads to increased carbon emissions and other harmful greenhouse gases in the atmosphere. This, in turn, accelerates global climate change while simultaneously intensifying the urban heat island

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(UHI) effect at the local scale (Nikolopoulou and Steemers, 2003; Oláh, 2012; Yuan et al., 2022; Agson-Gani, 2025). The phenomenon of UHI causes both surface and air temperatures in city centres to reach significantly higher levels than in surrounding rural areas. This situation has a negative impact on thermal comfort conditions in urban open spaces, which are crucial for human health (Yang et al., 2016; Qian and Li, 2023; Tağıl et al., 2024). A large number of scientific studies conducted on this subject have found that surface temperatures in densely built-up urban areas are significantly higher than in the surrounding rural landscapes. In this context, the continued and uncontrolled expansion of urban areas not only undermines ecological sustainability but also exerts adverse impacts on human health and overall quality of life (Kushwaha, 2021; Liu et al., 2022; Popa et al., 2022).

The literature has extensively demonstrated that high-rise development intensifies the UHI effect, with areas characterized by dense clusters of multi-storey buildings exhibiting substantially greater thermal loading compared to zones dominated by low-rise structures (Peng et al., 2012; Yao et al., 2017; Unsal et al., 2024). This situation is associated with a high degree of building density, which limits wind circulation and, consequently, reduces natural ventilation. This alters the balance between solar radiation and reflection and increases anthropogenic heat emissions (Lee et al., 2014; Diren et al., 2022). Research aimed at mitigating the heat stress specific to urban canyons indicates that strategies such as increasing vegetated areas, employing high-albedo surface materials, integrating shading plant species, and implementing blue–green infrastructure (BGI) systems are effective in reducing the intensity of the UHI effect and enhancing outdoor thermal comfort (Nuruzzaman, 2015; Oropeza-Perez and Østergaard, 2018; Lai et al., 2021; Yin et al., 2023; Ramer et al., 2025). Furthermore, a review of the literature reveals that strategies such as the implementation of reflective coatings, the incorporation of shade-providing vegetation, and BGI systems have been demonstrated to effectively mitigate the severity of the UHI, while also significantly enhancing outdoor thermal comfort conditions in urban areas (Gunawardena et al., 2017; Budzik et al., 2025). In this context, Land Surface Temperature (LST) a critical parameter for evaluating urban microclimatic conditions is an indicator derived from satellite-based remote sensing that reflects the thermal properties of surfaces and their contribution to the surface energy budget (Algretawee et al., 2019; Li et al., 2025). LST provides researchers with a significant analytical tool with which to determine the spatial patterns of the UHI by accurately revealing differences in building density, material properties, vegetation distribution, and shading conditions (Taloor et al., 2024; Xiong et al., 2025). Studies emphasize that, in particular, BGI solutions provide multifaceted benefits by reducing LST values, preventing flood events, and enhancing ecosystem services. Accordingly, accurately planning, designing, and managing the relationship between urban morphology and local climate supported by LST-based analyses is regarded as a critical determinant in the development of sustainable, climate-adaptive, and resilient cities (Hamel and Tan, 2022; Siehr et al., 2022; Lan et al., 2025).

The planning and design of green infrastructure systems aimed at mitigating the UHI effect require a comprehensive and detailed analysis of current climatic conditions and LULC (Zhang et al., 2018). In this process, the use of advanced simulation models capable of accurately representing microclimatic variables is crucial for ensuring that planning and design decisions at the urban scale are grounded in robust scientific evidence. While monitoring-based approaches provide a valuable analytical tool for assessing thermal comfort conditions in urban areas in relation to the UHI, LST analyses,

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in particular, constitute a critical indicator for revealing the intensity and spatial distribution of the UHI, as they objectively and spatially represent the thermal behavior of urban surfaces. LST provides a fundamental reference for the current state of the urban microclimate by accurately determining the thermal responses of different surface materials, vegetation density and shading conditions through remote sensing (Yan et al., 2024; Rahimi et al., 2025). Among the most widely employed methods for assessing urban thermal comfort in scientific studies, the ENVI-met model enables high-resolution spatial and temporal analyses of microclimatic variables (such as air temperature, relative humidity, wind fields, and mean radiant temperature (MRT) owing to its capacity to simulate interactions between the atmosphere, surfaces, and vegetation in three dimensions (Salata et al., 2016; Yılmaz et al., 2018). Thanks to its capacity to model atmosphere, surface, vegetation interactions in three dimensions, ENVI-met enables the analysis of microclimatic variables at high spatial and temporal resolutions and provides an important methodological framework for evaluating the effectiveness of green infrastructure strategies (Simon et al., 2018).

The aim of this study is to analyze the formation and dynamics of the urban heat island effect in the Paşaalanı neighborhood of Karesi district, Balıkesir province, using LULC and LST data, and to identify the potential role of green infrastructure applications in mitigating this effect using the ENVI-met simulation model. The study adopted a multi-scale analytical approach. In this context, LULC and LST data from 2000, 2013, and 2024 were analyzed to identify LULC changes and surface temperature trends in the neighborhood. This large-scale LULC and LST analysis provided the basis for the microclimatic investigations conducted in Paşaalanı Neighborhood; after examining the existing urban fabric within the identified sub-area, two different green infrastructure scenarios were developed. The first scenario is based on planting arrangements using deciduous species, while the second relies on coniferous species. The microclimatic impacts of both scenarios were comparatively analyzed using the ENVI-met model. The assessment of the existing conditions together with the proposed green infrastructure configurations aims to provide a scientific basis for planning and design processes by revealing the effectiveness of different plant species in mitigating the urban heat island effect. Additionally, this study is expected to contribute to the development of strategies and solution proposals for reducing urban heat islands in Paşaalanı Neighborhood, where building density has been increasing. The original contribution of this study arises from its integrated analytical framework, which evaluates the urban heat island effect through a multi-scale approach. LULC and LST analyses conducted at the neighborhood scale for the years 2000, 2013, and 2024 reveal the long-term thermal trends of Paşaalanı Neighborhood, while micro-scale ENVI-met simulations within a selected sub-area provide a detailed assessment of the impacts of green infrastructure scenarios on the local microclimate. The combined interpretation of LULC, LST and ENVI-met results offers a comprehensive framework rarely addressed in the literatüre on how regional thermal trends can be transformed through micro-scale interventions, and presents, for the first time in Balıkesir, a scenario-based urban climate assessment.

Materials and methods

Material

Residential buildings in Yaşamkent and the surrounding area, situated in the Paşaalanı neighbourhood which has been designated as the study area are located along the urban

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expansion axis of Balıkesir, one of Turkey's major provinces, and fall within the administrative boundaries of the Karesi district. The study area is geographically located between 39° 39′ 40.94″ and 39° 39′ 32.27″ north latitude and 27° 54′ 30.07″ and 27° 54′ 40.65″ east longitude. Over the past three decades, Paşaalanı Neighborhood has become a significant residential zone within the westward spatial growth trajectory of Balıkesir. Such peripheral expansion, commonly observed in medium-sized Anatolian cities, is often associated with increased development pressure along urban fringes and the consequent transformation of natural areas (Aydın, 2009; Güney, 2018). The population of Karesi district stood at 80,500 people in 2000, rising to 167,549 people by 2013. By 2024, the population had reached 190,427 people. Similarly, the population of Paşaalanı neighbourhood has also increased over the years. In 2000, the population of Paşaalanı Neighbourhood was around 9,000 people; by 2013, it had reached 21,119 people, and by 2024, it had reached 30,816 people. This demonstrates that there has been a significant increase in population over the years in both Karesi District and Paşaalanı Neighbourhood. The location of the study area and the images are shown in *Figures 1* and *Figure 2*.

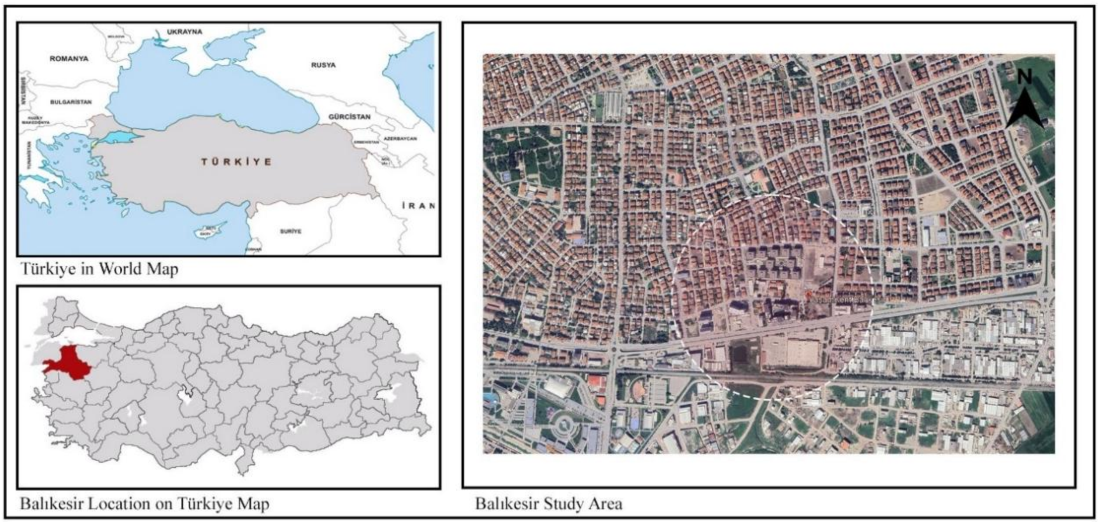

***Figure 1.** Location of the study area*

Prior to 2005, the study area was predominantly characterised by agricultural activities. However, following the issuance of planning permission from that date onwards, a rapid urban transformation process was initiated, resulting in a substantial increase in construction activities. Areas previously used for agricultural activities have been replaced by extensive impervious surfaces as a consequence of the urban development process. When the study area is evaluated in terms of its climatic characteristics, it is located within the transition zone between the Mediterranean and Marmara climates. This zone is defined by hot, dry summers and mild, rainy winters. The mean annual temperature ranges between 14 and 15 °C, while the average annual precipitation is approximately 600–700 mm (Balıkesir Regional Directorate of Meteorology, 2025). In recent years, temperatures exceeding 35 °C have become increasingly frequent during the summer months, thereby intensifying the urban heat island (UHI) effect, particularly in areas with high building density.

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Figure 2. *Images relating to the study area*

Methods

This study is structured around three main methodological stages, each comprising a series of analytical steps leading to the final results. In the first two stages of the method, LULC and LST analyses for the Paşaalanı neighbourhood were conducted for the years 2000, 2013 and 2024 using Remote Sensing (RS) and Geographic Information Systems (GIS). In the third stage of the method, the ENVI-met model is used to simulate 4-hour potential temperature dynamics for the current conditions within the study area and for two alternative vegetation scenarios. These scenarios include a design utilising coniferous species and a design utilising deciduous species. All the datasets obtained were subsequently evaluated in an integrated manner.

In recent years, the combination of LULC analysis, LST assessment and advanced RS techniques has emerged as an effective approach to understanding ecosystems in urban areas. Furthermore, the integrated use of RS and GIS plays a significant role in interpreting the relationship between LULC and LST (Lou et al., 2025; Arsiso, 2025).

In the first stage of the method, satellite imagery from 2000, 2013 and 2024 was used for LULC analysis, alongside the Random Forest (RF) algorithm, a machine learning-based classification method. The RF algorithm is among the most widely used classification methods in LULC analysis in recent years (Purwanto et al., 2022). RF is a classification method based on the combination of decision trees and is known for its high accuracy rates. Each decision tree performs calculations regarding the dominant class unit to classify specific classes based on the training data used as input (Avı et al., 2023; Ewunetu and Abebe, 2025). Within the scope of this study, LULC analysis was carried out in five main stages: data acquisition, creation of training/test datasets, calculation of spectral indices, classification, and accuracy analysis. Landsat 5 TM satellite imagery for the year 2000 and Landsat 8 OLI satellite imagery for the years 2013 and 2024 were used as the data set. Additionally, support was obtained from programmes such as Google

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Earth Engine and Google Earth Pro. In the study, separate models were trained using the training datasets created for each year, and land cover maps were generated by applying these models to the satellite imagery of the relevant year. To represent the land cover classes, 50 random points were selected for each class, and these points were used as reference data. In the classification, the study area was divided into three land cover classes. These classes were defined as Built-up, Vegetation and Bare land. During the classification process, the following spectral bands from the Landsat image were used: Blue, Green, Red, Near-Infrared (NIR), Short-Wave Infrared 1 (SWIR1) and Short-Wave Infrared 2 (SWIR2): Furthermore, to better distinguish land cover, the Normalised Vegetation Index, Normalised Built-up Index, and Bare Land Index spectral indices were calculated. These indices were derived using combinations of spectral bands and incorporated as inputs into the classification process.

An accuracy analysis was conducted to evaluate the performance of the classification results. In calculating the accuracy analysis, Producer's Accuracy (PA), User's Accuracy (UA), Overall Accuracy (OA) and the Kappa Coefficient (Baccari et al., 2024) were used. The accuracy analysis was carried out using the confusion matrix generated from the test datasets. The Kappa statistic was used to assess how much better the classification result was compared to random classification.

In the recent stage of the methodology, LST maps for the study area and its immediate surroundings were generated for the years 2000,2013 and 2024. The primary purpose of producing these LST maps was to examine the changes in surface temperatures that occurred within the district over a 24-year period and to enable a more in-depth interpretation of the thermal dynamics influencing the region.

For this purpose, the LST was derived using the thermal infrared (TIR), red, and near-infrared bands of Landsat satellite images from July 20–28. When using Landsat 5 TM sensor images for the year 2000, the red (Band 3), near-infrared (Band 4), and thermal infrared (TIR) (Band 6) bands were selected. In 2013, Landsat 8 data were used, and for this sensor, the red (Band 4), near-infrared (Band 5), and thermal (Band 10) bands were included in the analyses. Since Landsat 8 was also used for 2024, the bands were defined as red (Band 4), near-infrared (Band 5), and thermal (Band 10). The TIR bands of both sensors are highly sensitive to thermal radiation emitted from the Earth's surface, enabling the computation of Brightness Temperature (BT), which subsequently forms the basis for LST estimation. This approach provides a reliable and methodologically robust framework for extracting surface temperature information from multi-temporal Landsat datasets and for assessing long-term thermal variations within the study area. All satellite images were obtained within the scope of the Landsat Collection 2 Level-1 dataset to ensure data standardization and comparability. This dataset provides imagery that has undergone geometric and radiometric corrections, sensor calibration, and preprocessing suitable for temporal analyses. Thus, it enables consistent and reliable analysis of Landsat data across different years.

In cases where detailed land-cover information is not required, or when the primary objective of the study is to examine the spatial distribution of surface temperatures, it is common practice to adopt a constant surface emissivity value. In this approach, the thermal digital numbers (DN) were first converted into spectral radiance using the sensor-specific radiometric calibration coefficients. Subsequently, the radiance values were transformed into Brightness Temperature (BT) through the inverse Planck function, utilizing the K_1 and K_2 thermal calibration constants specific to each Landsat mission. Surface temperature was then calculated by applying the Single-Channel (SC) algorithm,

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in which BT is corrected using a constant emissivity value (ε = 0.98). The LST was obtained using the following equation:

Brightness Temperature (BT) was calculated using the following equation:

$$\mathrm{BT} = \frac{K_2}{\ln(K_1/\ \mathrm{L\lambda} + 1)} \tag{Eq.1}$$

In this equation;

K1, K2: Satellite sensor-specific calibration constants,

ln: Natural logarithm,

Lλ: spectral radiance,

BT: Brightness temperature (Kelvin).

LST was derived using the Single-Channel (SC) Method, which applies the following equation:

$$LST = \frac{BT}{1+(\lambda\times\frac{\mathrm{BT}}{\rho})\times\ln(\varepsilon)} \tag{Eq.2}$$

In this equation;

BT: Brightness temperature (Kelvin),

$\rho = 1.438 \times 10^{-2}$

ln: Natural logarithm,

ε = 0.98,

λ = the central (peak) wavelength of the thermal infrared band.

In the subsequent stage of the methodology, the ENVI-met model was employed to simulate the potential temperature distribution across the study area.

The ENVI-met model, developed by Michael Bruse in 1993, was designed to reproduce small-scale atmospheric conditions (Bruse and Fleer, 1998; Tsoka et al., 2018). The ENVI-met climate software is an advanced simulation model that has been used as a decision support tool in urban design processes, particularly in recent years. The ENVI-met model can be applied at various scales, ranging from a single building to a neighbourhood, with a maximum of 250 grids. The model has the ability to simulate surface-atmosphere interactions in urban environments with a typical horizontal resolution of 0.5–10 m (Bruse and Fleer, 1998; Ertem Mutlu and Yılmaz, 2024). With the newly developed plant-as-object approach, vegetation is no longer represented merely as dispersed grid cells characterized by leaf area density (LAD); instead, plants are modeled as integrated entities capable of interacting with and dynamically adapting to the surrounding environmental conditions (Krüger et al., 2011; Perini and Magliocco, 2014). This methodological innovation not only enables a more realistic assessment of plant atmosphere interactions but also facilitates the simulation of key microclimatic processes such as shading effects, modifications in wind flow, evapotranspiration dynamics, and radiation balance. The model plays a significant role in the detailed analysis of vegetation contributions to thermal comfort, the mitigation of urban heat island effects, and overall microclimatic regulation within urban environments (Ali-Toudert and Mayer, 2007; Faragallah and Ragheb, 2022).

In this study, a detailed methodological framework was adopted to enable a comparative analysis of the existing conditions and the proposed green space design scenarios. In the first stage, a comprehensive field survey was conducted to document the environmental and physical characteristics of the study area. This included the collection

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of site-specific spatial data alongside up-to-date meteorological observations obtained from radar, airport, and meteorological station records. To quantify potential temperature, meteorological data from July were utilized, and the relevant datasets were acquired from the Balıkesir Regional Directorate of Meteorology. In the second stage, the fundamental datasets required for the modeling process were prepared using the site plan obtained from the Balıkesir Metropolitan Municipality and high-resolution satellite imagery from Google Earth dated 2025. These datasets were subsequently integrated into a three-dimensional urban morphology model using the ENVI-met BIO+ Science version, through which the geometric configuration of the area, surface cover characteristics, and material parameters were defined in detail. As shown in *Table 1*, the ENVI-met model input data set comprises a series of variables pertinent to the study.

Table 1. *ENVI-met model ınput data*

Location	Balıkesir/Karesi
Climate type	Transition ecosystem
Simulation time	July
Total simulation duration	7:00 am, 10:00 am, 13:00 pm, 16:00 pm
Spatial resolution	2m x 2m x 2m
Study area size	167.390.16 m²

Two distinct green infrastructure scenarios were developed for the study. The first scenario is based on planting arrangements utilizing deciduous species, while the second scenario incorporates coniferous species. In the final stage, microclimatic outputs were visualised using the Visualise Results (Leonardo) module for spatial evaluation. Based on the prepared model inputs, INX (input) and SIMX (simulation) files were generated, and simulations were run for every 4 hours (7:00 am, 10:00 am, 13:00 pm, 16:00 pm). This numerical modelling enables the calculation of fundamental parameters at the microclimatic level, such as air temperature, relative humidity, wind speed, surface and wall radiation, and potential temperature. The total study area covers 167.390.16 m². In its current state, 27% of the area is occupied by buildings, while 32% is allocated to road infrastructure. In the second simulation, where deciduous species were integrated into the vacant areas, the proportion of green spaces increased to 12%. A comparable procedure was applied in the simulation involving the selection of coniferous tree species. In the existing condition, the absence of tree and shrub communities, along with the presence of only limited lawn surfaces and groundcover species, is noteworthy. However, due to the insufficient ecological functionality and spatial density of this vegetation, it was not included in the modeling and analytical processes. In addition, in the second scenario, deciduous tree species were introduced, consisting of 30 *Platanus orientalis* and 30 *Tilia tomentosa*. In the third scenario, coniferous species were used, including 30 *Pinus pinea* and 30 *Pinus nigra.* In both vegetation scenarios, a total of 60 trees were planted with a spacing of 5 m between trees. The trees were modeled with a height of 10 m and a crown diameter of 6 m and were evenly distributed across the study area to ensure consistent comparison of the cooling performance of different vegetation types. The method flow chart is presented in *Figure 3*.

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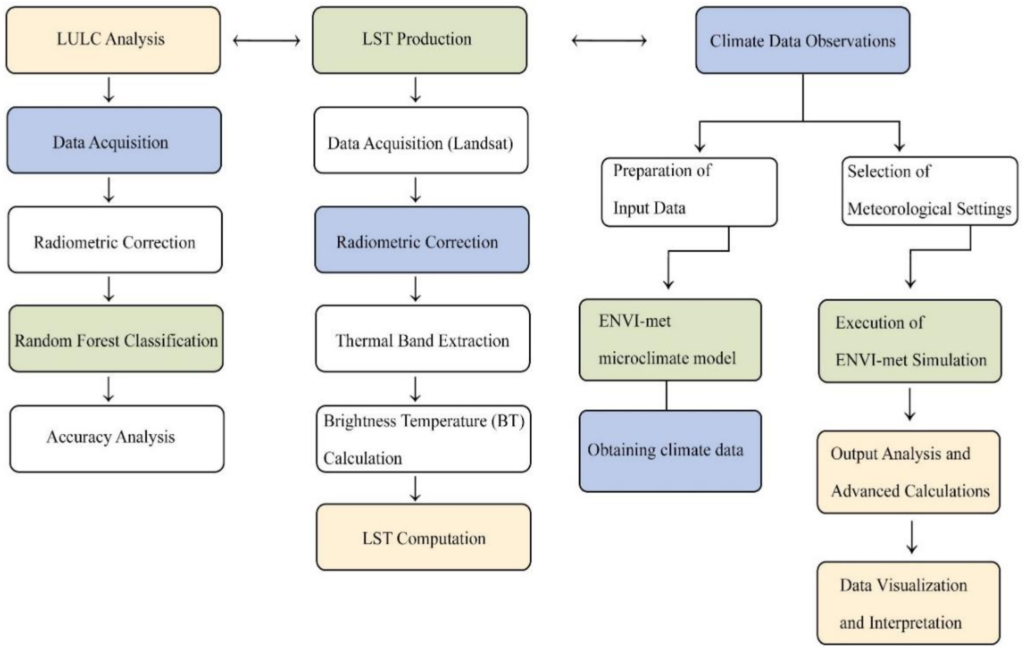

Figure 3. *Method flow chart*

Results

An examination of the temporal changes in the LULC analyses for the years 2000, 2013 and 2024 reveals, as shown in *Figure 4*, that the Paşaalanı neighbourhood and the study area have been affected by urban development, and that urban green spaces have gradually given way to further development over time. When LULC changes are examined on a hectare-by-hectare basis (*Table 2*), it is evident that built-up areas within the study area increased significantly between 2000 and 2024. Built-up areas increased by 57.1% between 2000 and 2013, and by a total of 58.8% between 2000 and 2024. The decline in vegetation areas over time is striking. A decrease of 64.8% occurred between 2000 and 2013, and a decrease of 75.3% between 2000 and 2024. This situation indicates an intensive land conversion process, particularly during the initial period (2000–2013). When bare land areas are examined, a 50.7% increase was observed during the 2000–2013 period, whilst a 13.2% decrease occurred during the 2013–2024 period. Nevertheless, there has been a net increase of 30.9% in bare land areas over the 2000–2024 period as a whole.

The overall accuracy and Kappa coefficient values, which were primarily used in the accuracy analysis, were calculated when evaluating the land use and land cover (LULC) classification results for the years 2000, 2013 and 2024 (*Table 3*). The calculation results revealed that the highest overall accuracy (97.7%) and Kappa coefficient (0.96) values were recorded for the year 2024.

In the study, a comparative analysis of LST distributions for the years 2000, 2013 and 2024 was carried out at neighbourhood level, revealing a significant change in temperature between the three periods (*Figure 5*). It was determined that the LST values for the three years examined in the study ranged from 33.20 to 40.31 °C. Furthermore, it was observed that surface temperatures within the 38.50–40.31 °C range were recorded over a wider area between 2000 and 2024. This indicates that LST values have increased in line with the growing level of urbanisation in the neighbourhood. Furthermore, LST

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values in the area of the selected Yaşamkent residential buildings within the neighbourhood were measured at 33.20–35.57 °C in 2000, 36.66–37.52 °C in 2023, and 38.00–40.31 °C in 2024. The rise in temperatures observed in the Paşalanı neighbourhood and the Yaşamkent residential buildings can be regarded as the result of multifaceted environmental processes. However, LULC analyses reveal that, over a 24-year period, LST values have also increased as a result of built-up development.

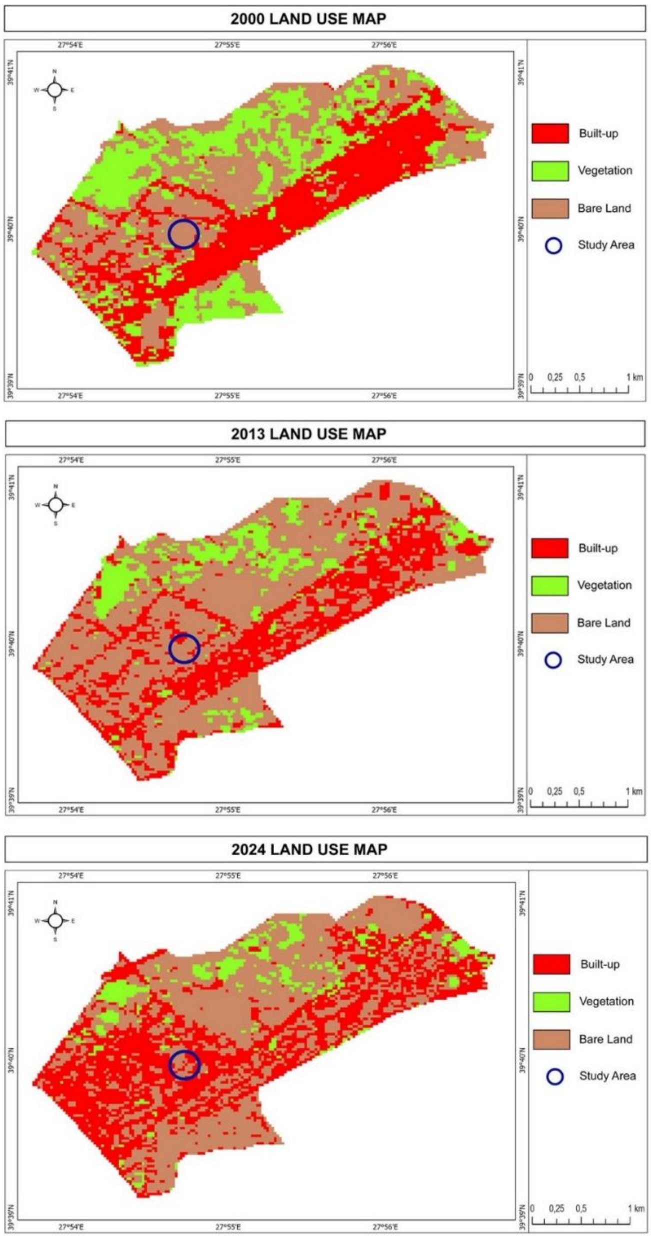

Figure 4. *LULC maps for the years 2000, 2013 and 2024*

Table 2. *Changes in land use/cover between 2000, 2023 and 2024, expressed in hectares*

Year	Built-Up	Vegetation	Bare Land
2000	240.04	332.25	353.16
2013	277.38	117.81	532.26
2024	381.78	82.89	462.78

***Table 3.** LULC classification accuracy analysis*

Years	Overall accuracy	Kappa Coefficient	Built-up Area (PA / UA)	Vegetation (PA / UA)	Bare land (PA / UA)
2000	%95.9	0.93	%91.6 / %91.6	%95.2 / %95.2	%100 / %100
2013	%96.5	0.94	%92.3 / %100	%100 / %100	%100 / %88.8
2024	%97.7	0.96	%100 / %100	%100 / %93.7	%93.7 / %100

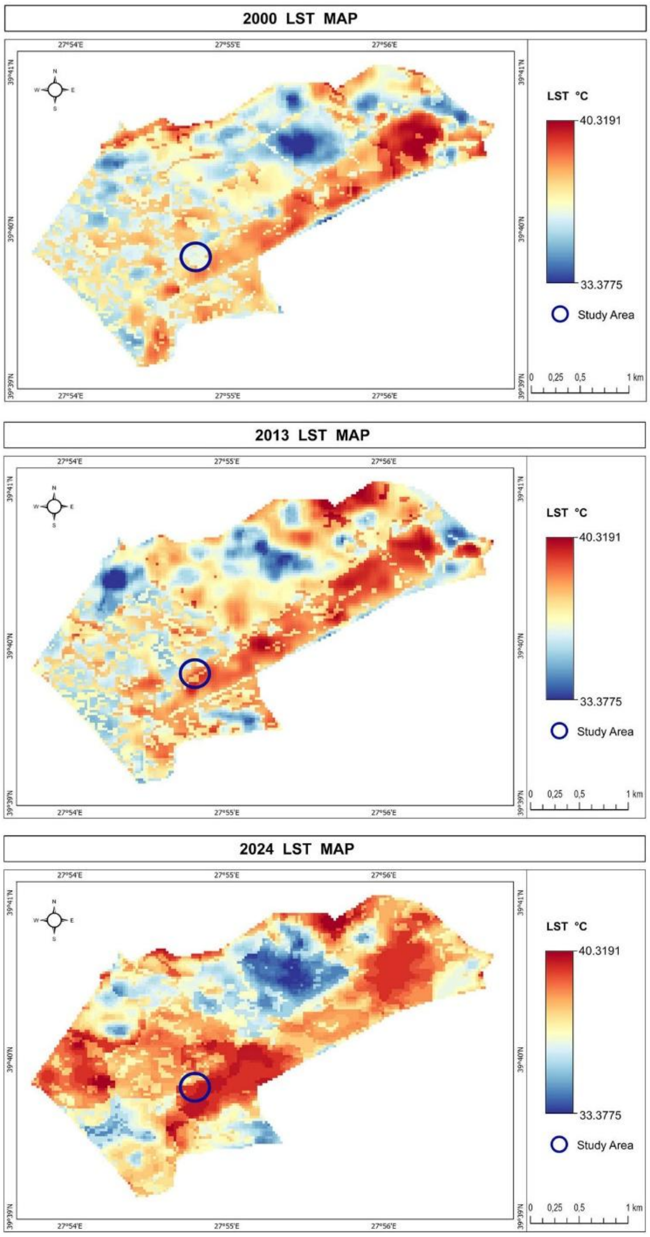

***Figure 5.** LST maps for the years 2000, 2013 and 2024*

Moreover, the primary rationale for employing LST analysis in this research lies in its capacity to integrate small-scale temperature variations with broader (neighbourhood or district) thermal dynamics. In doing so, microclimatic changes can be interpreted more objectively and consistently in relation to regional thermal patterns, enabling a more

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robust assessment of spatial temperature heterogeneity and its environmental implications.

In the next stage of the study, three scenarios were designed (*Figure 6*) using the ENVI-met microclimatic simulation software to evaluate the potential contributions of green infrastructure practices in mitigating the urban heat island (UHI) effect, and the study area was selected as Yaşamkent residential buildings and its immediate surroundings, located in the Paşaalanı neighbourhood of Balıkesir Province.

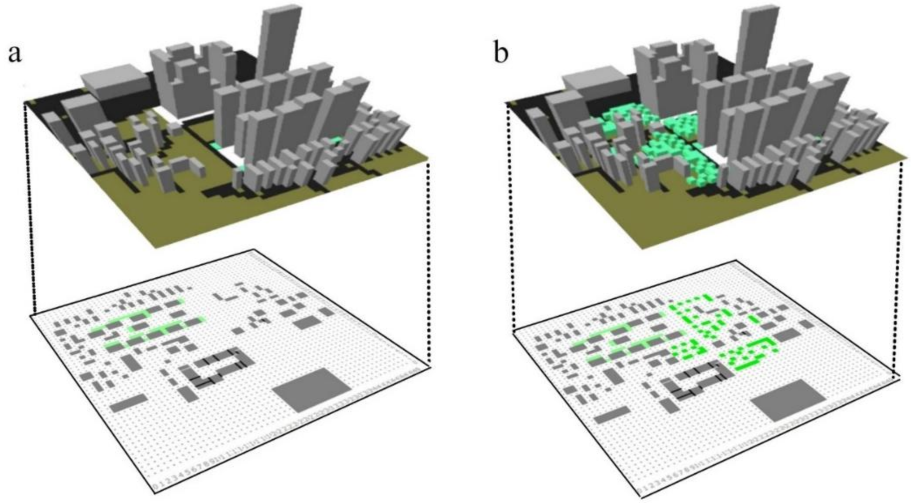

Figure 6. *(a) Existing condition of the study area. (b) Vegetation design scenario developed for ENVI-met simulations. In the design scenario, the planting areas were kept identical to the existing layout, while only the tree species were modified to represent deciduous and coniferous alternatives*

In the study, the first scenario represents the existing spatial condition characterized by a high proportion of impervious surfaces and limited vegetative cover. In the second scenario, the green infrastructure was enhanced by integrating deciduous tree species into currently vacant urban spaces. The third scenario, in contrast, involved the incorporation of coniferous tree species into the same areas. All three scenarios were modeled over a 4-hour period, and the resulting outputs were mapped through ENVI-met's Leonardo module and subjected to comparative analyses. In the comparative evaluation of the three scenarios, potential air temperature distributions were assessed using the map outputs corresponding to morning hours (07:00 and 10:00), noon (13:00), and afternoon (16:00). The evaluation results are presented in *Figure 7, Figure 8, Figure 9, Figure 10*.

An examination of the simulation outputs obtained at 07:00 (*Figure 7*) reveals no substantial differences in potential air temperature between the existing condition and the proposed scenarios. The observation that the minimum and maximum potential temperatures of the Baseline, Deciduous Vegetation, and Coniferous Vegetation simulations range between, 22.59–23.73°C, 22.40–23.74 °C and 22.41–23.73 °C respectively, is directly associated with the fact that solar radiation has only limited influence on surface heating during this early time period. In other words, during the early morning hours, both atmospheric and surface energy balances remain largely influenced by longwave radiative cooling processes that occur overnight. As a result, the distinct thermal characteristics of asphalt, concrete, and vegetated surfaces have not yet become

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pronounced. This finding indicates that the thermal behavior of urban surface materials exhibits a relatively homogeneous pattern at this time of day. As the duration and intensity of solar exposure increase, the heat storage and conduction properties of different surface materials begin to dominate, leading to more pronounced differences among the scenarios later in the day. Therefore, the absence of statistically significant variation during the morning hours highlights the limited discriminative power of early-morning measurements in urban microclimate modeling, while emphasizing that the most meaningful divergences emerge during midday and afternoon periods. However, the coniferous vegetation simulation reveals a localized concentration of higher temperatures in the western sector of the study area, suggesting that vegetation structure and shading patterns may influence early-morning thermal distributions.

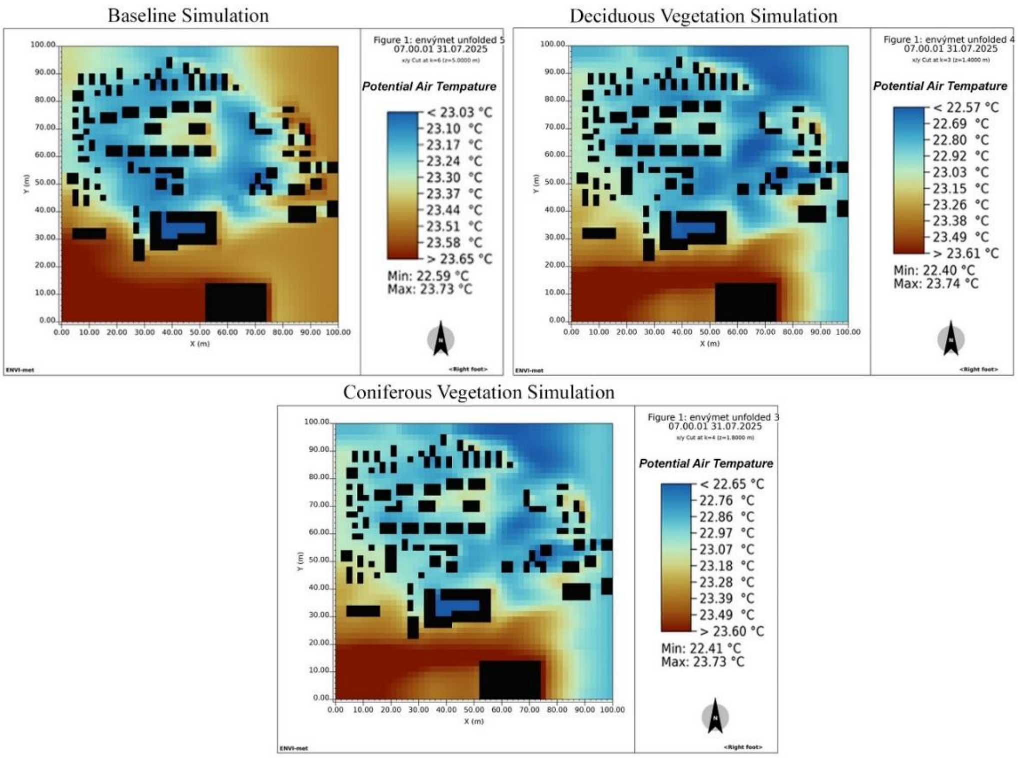

Figure 7. *ENVI-met model simulations for the 07:00 a.m. time step*

Analysis of the ENVI-met outputs at 10:00 reveals that distinct spatial variations in potential air temperature have begun to emerge among the Baseline, Deciduous Vegetation, and Coniferous Vegetation scenarios (*Figure 8*). These differences coincide with the increase in solar altitude, which enhances the influence of surface material heat-storage properties as well as vegetation-driven shading and evapotranspiration in shaping the thermal structure of the urban environment. The Baseline Simulation map indicates a notable concentration of higher temperatures, particularly in the southern and southwestern sections of the study area. This thermal accumulation results from the rapid absorption of solar radiation by unshaded impervious surfaces, leading to elevated potential air temperatures at this time of day. In contrast, the Deciduous Vegetation Simulation demonstrates a broader distribution of cooler temperature zones relative to the Baseline scenario. This pattern reflects the growing shading capacity of deciduous trees

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during the morning hours, coupled with the initiation of evapotranspirative cooling, both of which contribute to a more homogeneous and cooler microclimate at ground level. While the Coniferous Vegetation Simulation also exhibits a general cooling trend, a localized hotspot becomes apparent in the western portion of the study area, suggesting that canopy structure and airflow reduction associated with coniferous species may induce localized thermal accumulation despite their overall cooling contribution.

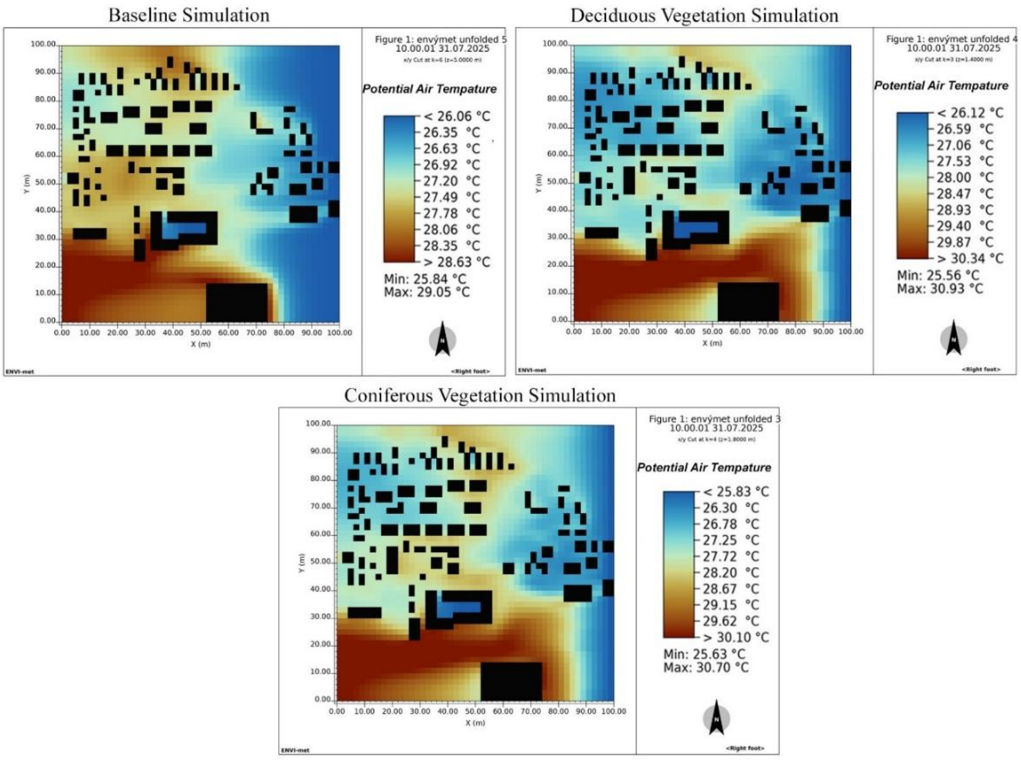

Figure 8. *ENVI-met model simulations for the 10:00 a.m. time step*

The ENVI-met simulation conducted for 13:00 corresponding to the period of maximum solar incidence in July reveals pronounced thermal variations across the study area under different vegetation scenarios (*Figure 9*). July, characterized by its exceptionally high radiative load, prolonged sunshine duration, intense short-wave radiation, and minimal cloud cover, intensifies surface heat accumulation, thereby amplifying microclimatic differences between the scenarios.

In all three scenarios, the potential air temperature shows an increasing trend from north to south. This pattern is attributable to the elevated position of the sun in the sky during July, which exposes south-facing surfaces to longer durations of direct solar radiation. Deciduous trees, which reach maximum foliage density in summer, effectively reduce short-wave radiation input in northern sections through extensive shading. However, toward the south, increased solar exposure and higher radiative forcing enhance surface heat storage, leading to progressively higher temperature values in that direction.

In contrast, the scenario incorporating coniferous tree species generates a distinct thermal pattern under the intense radiative conditions of July. Compared to the baseline scenario, the presence of coniferous trees contributes to the formation of relatively cooler areas, indicating a measurable cooling effect. However, this cooling remains less

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pronounced than that observed in the scenario with deciduous tree species. In particular, at 13:00, when shortwave solar radiation reaches peak levels, the lowest potential air temperatures are observed in the deciduous tree scenario, whereas the coniferous scenario exhibits comparatively higher temperature values. This difference can be attributed to the limited horizontal shading provided by coniferous trees, whose year-round foliage and narrow, vertically oriented crown structures reduce their effectiveness in mitigating midday solar radiation. The quantitative results further substantiate these microclimatic distinctions. The deciduous tree scenario records the lowest minimum potential air temperature at 28.70 °C, reflecting a slight reduction in air temperature despite July's extreme radiative conditions. By comparison, the baseline and coniferous scenarios exhibit higher minimum temperatures of 28.72°C and 28.77°C, respectively. Moreover, the coniferous tree design scenario encompasses a larger spatial extent of areas with temperatures exceeding 31.52 °C compared to the deciduous tree design scenario. Furthermore, in this scenario, high temperature values are particularly concentrated along the west-central axis of the working area.

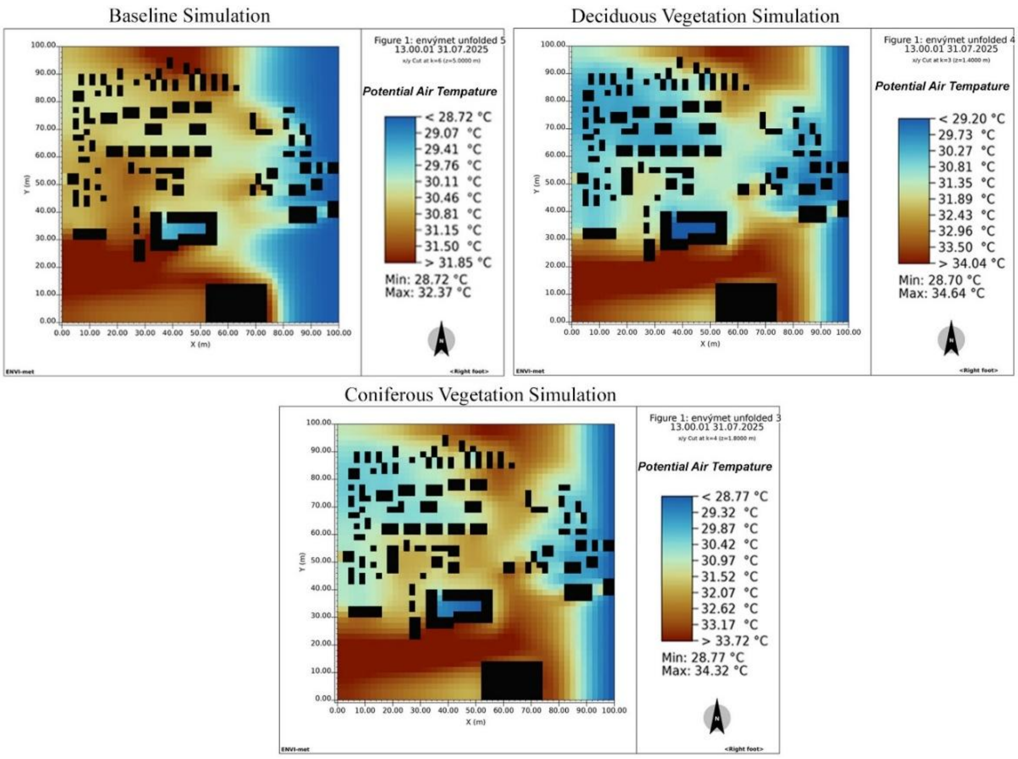

Figure 9. *ENVI-met model simulations for the 13:00 p.m. time step*

The 16:00 data clearly reveal the thermal differentiation among the scenarios (*Figure 10*). In the baseline scenario, the continued radiative heat release resulting from the high heat storage capacity of impervious surfaces such as asphalt and concrete leads to pronounced thermal disadvantages that persist even during the afternoon hours. In contrast, in the scenario incorporating deciduous vegetation, the cooling effect of green spaces becomes evident, as indicated by the dominance of blue tones in the temperature distribution maps, reflecting a more thermally balanced environment at the spatial scale. In this proposed scenario, the microclimatic regulation effect is observed to be stronger

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and more widespread due to the shading and evapotranspiration processes provided by the vegetative cover. The prevalence of blue tones in the maps not only signifies an immediate cooling effect but also indicates the presence of a sustained cooling potential that continues into the later hours of the day. In the scenario where coniferous tree species are selected, a gradual decrease in temperature from west to east is observed.

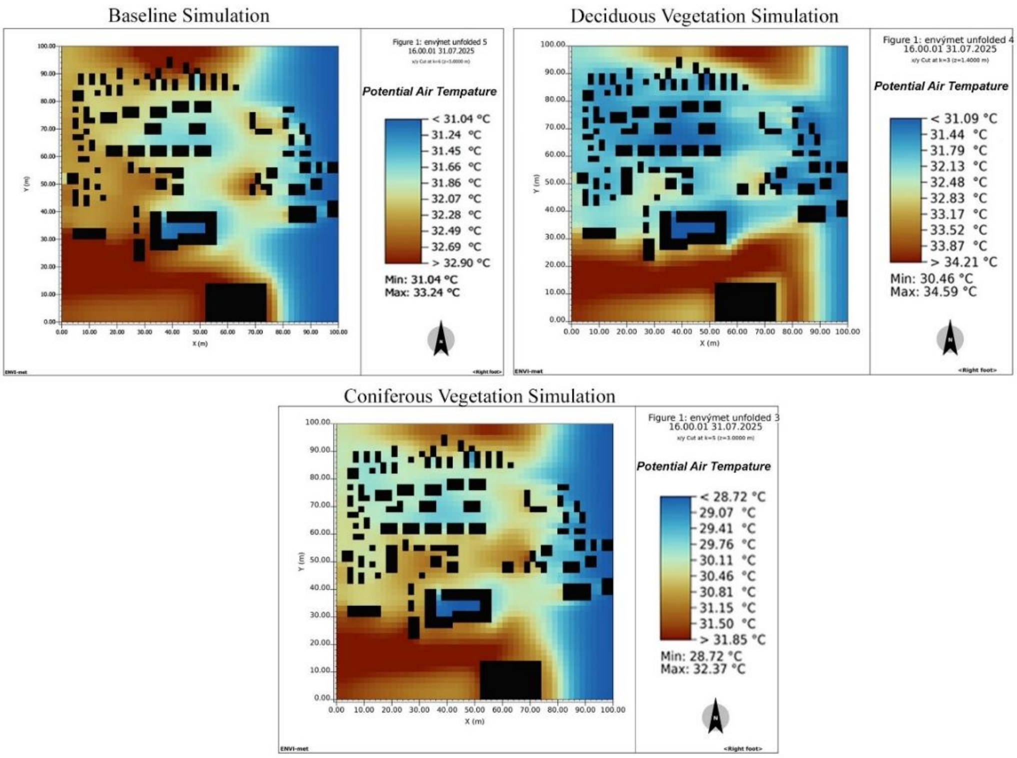

Figure 10. *ENVI-met model simulations for the 16:00 p.m. time step*

Discussions

In this study, spatial and temporal changes in the region were identified through LULC and LST analyses conducted at a larger scale; based on these analyses, the importance of green infrastructure in mitigating potential temperature increases was highlighted. Based on the findings, different design scenarios prioritising green infrastructure were developed for a sub-study area selected at a smaller scale, and the effects of these scenarios on microclimatic conditions were examined. Thus, an assessment was made of the design approaches through which green infrastructure could be implemented to reduce urban temperatures. There are numerous scientific studies in the literature that evaluate LST and LULC analyses conducted at a larger scale in conjunction. For example, in their study, Patel et al. (2024) investigated the effects of LULC and LST on outdoor thermal comfort. Findings based on peer-reviewed literature from the past 24 years demonstrate that LULC significantly influences urban thermal environments. Furthermore, the study identified strategies such as increasing vegetation cover, managing surface albedo and optimising urban form as effective approaches for reducing urban heat and improving outdoor thermal comfort. Dissanayake (2020) examined the relationship between LULC and LST over a 23-year period in the coastal city of Galle, Sri Lanka. Analyses using Landsat data and the Random Forest classification method showed that as built-up areas

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increased and vegetation cover decreased, LST rose in parallel. In their study, Feng et al. (2025) examined the temporal changes in pasture areas in the Khushab and Bhakkar districts of the Punjab region between 2000 and 2020, using LULC, LST and vegetation indices. The findings indicate that land-use changes and climate variability exert significant pressure on ecosystems in semi-arid regions.

It is observed that between 2000 and 2024, there was a 75.3% decrease in areas covered by vegetation in the Paşaalanı neighbourhood, whilst the rate of built-up increased by 58.8% over the same period. These changes in land use represent a highly risky situation for the urban ecosystem. Over the 24-year period, it has been observed that LST values in the neighbourhood have also increased in a similar manner due to the effects of urbanisation. The LST values measured in residential buildings in Yaşamkent and its immediate surroundings (33.20–35.57 °C in 2000, 36.66–37.52 °C in 2023, and 38.00–40.31 °C in 2024) demonstrate the necessity of strengthening green infrastructure in this area.

In this study, 4-hour ENVI-met simulations representing July conditions were carried out for residential areas in Yaşamkent, which have undergone intensive development between 2000 and 2024. Within this scope, the effects of different vegetation cover design scenarios on the urban microclimate at 07:00, 10:00, 13:00 and 16:00 were evaluated comparatively. The findings indicate that, across all analyzed time intervals, the scenario incorporating deciduous tree species generated more extensive areas characterized by lower air temperature values compared to both the bare land scenario and the scenario dominated by coniferous tree species. This pattern is clearly reflected in the temperature distribution maps, where blue tones indicating cooler conditions are markedly more dominant.

The primary factor behind this outcome is the combined effect of the dense shade created by deciduous trees during the summer season and their high evapotranspiration capacity. From the early morning hours onward (07:00 and 10:00), the canopy limits the amount of incoming shortwave solar radiation reaching ground surfaces, thereby delaying surface heating. During midday (13:00) and afternoon hours (16:00), this effect becomes more pronounced, as the vegetation significantly suppresses the release of heat accumulated throughout the day. These results confirm that deciduous tree species exert a decisive cooling influence on urban microclimate under summer conditions.

In contrast, the temperature reductions observed in the scenario employing coniferous tree species were more limited when compared to those achieved in the deciduous tree scenario. This difference may be explained by the relatively lower leaf area index and reduced evapotranspiration capacity of coniferous species during the summer period, despite their year-round foliage.

Overall, the comparative results clearly demonstrate that strategically planned green infrastructure interventions can significantly reduce potential air temperatures in urban environments. The integration of deciduous trees into vacant urban spaces emerges as an effective strategy for mitigating the urban heat island effect, preventing excessive heat accumulation, and enhancing outdoor thermal comfort. These findings support the notion that the incorporation of vegetative green infrastructure into urban planning processes is not only ecologically beneficial but also a strategic necessity for climate-responsive and sustainable urban development.

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Conclusions

The role of green infrastructure components in mitigating the urban heat island effect has been extensively addressed in the literature for a long time. In this context, recent studies have clearly demonstrated that plant species selection directly affects microclimatic performance through its shading potential and evapotranspiration capacity. Increasing green spaces in urban areas plays a significant role in lowering surface temperatures and improving the microclimate by dispersing accumulated heat.

In this study, the temporal changes in LULC and LST values were examined using a multi-scale analytical approach. LULC and LST data for the years 2000, 2013 and 2024, analysed at the neighbourhood level, indicate that surface temperatures have risen over the past 24 years in areas of the study area where urbanisation has increased and vegetation cover has decreased. A comparative analysis of the green infrastructure scenarios proposed within the scope of ENVI-met simulations revealed that the scenario dominated by deciduous tree species had more positive effects on the microclimate. Simulations conducted specifically under July conditions show that cooler microclimatic areas are formed in this scenario and that cooler areas are significantly increased in temperature distribution maps.

Consequently, the systematic integration of green infrastructure approaches into planning and design processes is crucial for mitigating the urban heat island effect and adapting to climate change. Furthermore, green infrastructure approaches stand out as an effective tool for enhancing adaptation and resilience to climate change, making significant contributions to the creation of healthy and sustainable urban environments. In light of the findings obtained from the study, it is recommended that planning and design decisions be developed by considering the type, density, and spatial distribution characteristics of green infrastructure components in efforts to reduce the urban heat island effect.

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