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Impact of Urban Surfaces on Microclimatic Conditions and Thermal Comfort in Burdur, Türkiye

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Abstract: Rapid urbanization worldwide offers numerous benefits but also introduces challenges, particularly concerning urban climate comfort, which affects the physical and social well-being in cities. This study examined the microclimatic characteristics of the Burç neighborhood in the historical core of Burdur city, using ENVI-Met models with temperature, relative humidity, wind and PET data collected over a 33,665 m^2 area at 06:00, 09:00, 12:00, 15:00, 18:00 and 21:00 on 15 August 2023. The analysis revealed that thermal comfort decreases significantly from 09:00 onwards, especially on hard surfaces like asphalt, concrete and parquet, which lack vegetation and intensify heat retention. By contrast, green areas were found to enhance bioclimatic comfort by reducing perceived temperatures by up to 20% in shaded and vegetated zones. Based on these findings, it is recommended that urban areas reduce heat-absorbing materials, such as asphalt and concrete and prioritize green spaces in landscape planning to improve thermal comfort and create more sustainable urban environments.

Keywords: urban; climate; microclimate; environment; land use

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1. Introduction

Cities, among the largest human-made structures in the world, are home to more and more people every day. The phenomenon of urbanization, which is realized by the migration of the population living in rural areas to cities, is gradually increasing. In fact, while 55% of the world's population lives in cities today, it is estimated that this rate will increase to 68% by 2050 and 2.5 billion more people will reside in cities [1]. The increasing population and construction in cities lead to a decrease in green and open spaces. With the decrease in natural areas and permeable surfaces, artificial and impermeable areas have increased, which affects the urban climate [2]. Urban heat islands are formed with the increase in the density of heat-absorbing buildings and concrete surfaces as a result of surface changes [3–7]. The concept of urban heat islands, which occurs when the temperature in the urban area is higher than the rural area due to heat absorption, was first used by Luke Howard for the city of London in 1820 [8,9].

Urban heat islands, resulting from the difference in absorbed energy and the diversity in asphalt, concrete and building materials, create a different albedo effect between the city and its surroundings and lead to temperature differences [10]. The severity of urban heat islands caused by the temperature difference between the urban environment and the rural environment increases after sunset and becomes more pronounced, especially during calm and non-cloudy nights [11].

Air flows and wind speeds are influenced by the urban built environment with the decrease in open-green areas and increase in concrete surfaces in cities. In addition, the size and geometry of the buildings, streets and trees are critical factors for the formation of urban heat islands [12,13]. In addition, the heat capacity of building materials and anthropogenic heat emissions are other factors influencing urban heat island formation [14]. In this context, microclimates formed in urban areas according to their surroundings affect the thermal comfort of people [15].

According to studies conducted around the world, it is estimated that the temperature of countries located in mid-latitudes such as Turkey may increase by 1–6 °C in the 2099s [16]. In order to minimize this increase and provide thermal comfort, green-open spaces should be protected and expanded as much as possible and planting activities should be increased [17–19] In particular, trees, shrubs and ground covers, which are the prominent elements of green areas, should be increased to reduce surface temperatures and increase thermal comfort [20–22].

The size and variability of urban heat islands can vary due to heterogeneous land use, surface characteristics and macroclimatic conditions [23,24]. However, some researchers have conducted various studies on whether urban heat islands are beneficial or not. As a matter of fact, ref. [12] stated that in regions with a cold climate, urban heat islands can provide benefits such as reducing heating costs and combustion for heating purposes, reducing atmospheric phenomena such as surface icing and fog, increasing outdoor comfort, providing habitat for animals and accelerating plant growth during cold seasons. In addition, in hot climates or seasons, heat islands increase heat stress, increase the risk of mortality by creating an unhealthy thermal comfort environment for humans and can increase energy demand due to cooling [12,25–27].

When parameters such as temperature, humidity and wind in the environment are at a level where individuals feel comfortable, it means that the climate is comfortable [28–30]. In recent years, changes in climate comfort in cities have been observed as a result of heat islands. When negative effects such as thermal stress increase, disorders that may lead to death can occur [31]. To ensure bioclimatic comfort for urban residents, it is essential to determine climate parameters. In areas lacking climate comfort, physical and social problems arise and extra energy is spent for cooling [32]. Although thermal comfort is a subjective evaluation and a state of mind that reflects satisfaction with the thermal environment, the general opinion is that the temperature should be around 37 °C to prevent risky thermal stress in the human body [33]. More than 100 experiments have been conducted to measure climate comfort in the human environment using different senses. Among them, Temperature and Humidity Index (THI), Wind Efficiency Index (WEI) and Dressing Index have been widely used [34–36].

PET, Physiological Equivalent Temperature, allows for the calculation of the temperature felt in a given space. Thanks to PET, perceived climate comforts can be determined. In this way, the negative effects of climate parameters on people can be minimized. In particular, as a result of the studies, knowledge about diseases that are adversely affected by extreme heat or cold and humidity provides people with the opportunity to move to the places that are suitable for them. In addition, PET studies enable the creation of healthy environments according to the perceived climate comfort for people with chronic diseases and those over a certain age.

Almost all cities in Turkey, either large or small, are rapidly warming and exceeding the optimum temperatures [37]. Climate comfort risks should be measured and monitored to ensure climate comfort and to help carry out research on the interactions between health and global change [38]. In order to determine climate comforts in urban areas, detailed analyses can be conducted with the 3D ENVI-Met model [39].

Burdur was selected in order to emphasize its unique microclimatic conditions and historical context. The city's climatic characteristics, including its hot summers and minimal vegetation cover in urban cores, make it an illustrative example for studying urban heat island (UHI) effects and evaluating thermal comfort. Unlike larger Turkish urban centers, Burdur presents a typical medium-sized Mediterranean climate profile, providing a balanced view of UHI effects without the extremes seen in mega-cities. Analyzing Burdur can offer insights into strategies applicable to other medium-sized cities with similar climates, where urban planning adjustments for enhanced climate resilience are increasingly critical due to projected climate warming in mid-latitude regions like Turkey. Thermal comfort of the urban area was measured with the 3D ENVI-Met model using temperature, relative humidity, wind and PET data. Through this, the relationship between nature and thermal stress was determined and climate comfort characteristics were revealed. Furthermore, in this study, suggestions are given regarding considerations for urban planning in order to increase the thermal comfort of Burdur city.

2. Materials and Methods

Burdur (Türkiye) as the Illustrative Example

The study area is located in the Burç neighborhood in the Central district of Burdur province in the Mediterranean region of Türkiye. The study area is located between 37°43′06″ north latitude and 30°16′55″ east longitude. The study area has a total size of 33,665 m^2 (Figure 1).

Figure 1. Study area.

Burdur is located in Türkiye's Mediterranean region and exhibits typical Mediterranean climate characteristics. This climate is marked by hot, dry summers and mild, rainy winters. Especially during the summer months, the city experiences high temperatures and low humidity, making it conducive to the formation of microclimatic variations within the urban area. The limited vegetation cover and extensive use of hard surfaces in the city center further accentuate the urban heat island (UHI) effect in Burdur.

These regional climatic conditions make Burdur an ideal case study for microclimatic analysis. The findings from this study can offer insights for medium-sized cities with similar Mediterranean climates, helping inform strategies to enhance climate resilience in urban planning. Therefore, Burdur was selected as the study area, considering the unique climatic features of the region.

Meteorological data (temperature, humidity, wind direction and speed) for the study area were obtained from the Turkish State Meteorological Service. ENVI-Met 5.6.1 software was used to model these data. The selection of parameters used in the ENVI-Met model, including temperature, relative humidity, wind speed and PET, was based on regional climatic characteristics specific to Burdur. Historical meteorological data obtained from the Turkish State Meteorological Service were used to ensure the model's alignment with local conditions and to enhance the accuracy of the microclimatic analyses. Through the ENVI-Met model, where scenarios can be produced in order to identify the microclimate characteristics of cities and harmonize them with their environment, studies can be carried out at different scales. These can sometimes be applied on a small parcel or island in the urban areas, or they can cover larger residential areas. As a matter of fact, sometimes a university campus, sometimes a park area and sometimes the microclimatic characteristics of the historical core of the city can be analyzed through the ENVI-Met model and various scenarios can be produced. In this research, the microclimatic characteristics of the historical center of Burdur city were analyzed and corresponding models were produced through ENVI-Met using the temperature, relative humidity and wind data of the urban area in question.

Meteorological data used in ENVI-Met software for modeling are given in Table 1.

Table 1. Climate data used for ENVI-Met simulation.

Variables	Feature
Minimum temperature	19.6 °C
Maximum temperature	37 °C
Wind direction	North–northeast (33 degrees)
Wind speed	1.8 m/s
Minimum relative humidity	15
Maximum relative humidity	45

The input data to be used for modeling in ENVI-Met software were prepared in QGIS software (version 3.34.12). The numerical data prepared in QGIS software (version 3.34.12) were modeled with the QGIS Geodata to ENVI-Met plug-in. The QGIS Geodata plug-in was utilized to integrate spatial data from QGIS into the ENVI-Met model, enabling precise spatial analysis of the study area's microclimatic characteristics. This integration facilitated the transformation of QGIS data into ENVI-Met-compatible formats, ensuring consistency in the spatial dimensions of the analyzed data. In the modeling, the potential temperature, wind speed and direction, relative humidity and PET index of the study area were calculated and felt temperature maps were created.

To validate the accuracy of the ENVI-Met model outputs, a comparison was conducted with limited on-site measurements, particularly for critical parameters such as temperature and relative humidity. This validation process ensured the reliability of the simulated microclimatic conditions, reinforcing the model's application for urban heat analysis.

In this study, PET (Physiological Equivalent Temperature) is a temperature index measured in °C and is widely used to measure the temperatures felt by people living in different climatic zones [40–43]. In general, PET enables the climate environment analyzed in a specific region to be analyzed in a narrow area in an easily understandable and interpretable way [44]. The PET index calculates the temperature, solar radiation, humidity and wind of the thermal environment and the thermo-physiological conditions of the human body [45,46]. Thanks to the PET index, the effects of climate on the human body can be evaluated by considering the coefficients such as physical activity, physical fitness, age, weight and height [47]. In this respect, ref. [41] considered the coefficients according to the average height and age of 35 years old, 175 cm tall man, 0.9 CLO clothing load and 80 W workload while creating the PET index. In this context, bioclimatic comfort ranges were determined based on the calculated PET values, thermal sensation and stress levels [41,42] (Table 2). Human thermal sensation and stress ranges of PET are categorized as very hot to cold when determining temperature values. In this study, the monthly averages of thermal comfort conditions (PET) and meteorological parameters such as monthly temperature, humidity and wind were calculated.

Table 2. Human thermal sensation and stress ranges of PET [41,42].

PET (°C)	Thermal Sensation	Level of Thermal Stress
<4	Very cold	Extreme cold stress
4.1–8	Cold	Strong cold stress
8.1–13	Cool	Moderate cold stress
13.1–18	Slightly cool	Slight cold stress
18.1–23	Neutral (comfortable)	No thermal stress
23.1–29	Slightly warm	Slight heat stress
29.1–35	Warm	Moderate heat stress
35.1–41	Hot	Strong heat stress
>41	Very hot	Extreme heat stress

PET: Physiological Equivalent Temperature.

3. Results and Discussion

The existing urban land use in the study area is shown in Figure 2. The study area is 33,665 m^2 and has different components such as seating areas, squares and green areas. The square (Cumhuriyet Square) located in the center of the site has a large area including roads and hard surfaces. In addition to hard surfaces, there are Pinus pinea and Cedrus libani trees in terms of vegetation in the study area. The number of floors of the houses in the study area varies between one and four and the most common number of floors is four. The lowest number of storeys is one (building no. 6) in the central northern part of the study area, while a two-storey building (no. 7) is located in the eastern part. The most common number of storeys is four and these buildings are located in the southeast, southwest and northwest sections of the study area. The green area is located in the central northern part of the site.

The land use types in the study area are categorized into vegetated areas, hard surfaces (such as asphalt and concrete) and built-up areas. These classifications were made based on surface characteristics observed in field surveys and satellite imagery analysis. Vegetated areas are marked with green shades, representing parks and tree-covered zones, while hard surfaces, which include roads and pavements, are indicated with gray shades. Built-up areas are denoted by darker shades to reflect structures like residential and commercial buildings. The legend has been adjusted to clearly distinguish these categories for a more accessible interpretation of land use distribution in the study area.

The data used in the study belong to 15 August 2023 and the analysis and evaluations in the study are based on the measurements obtained on this date. The reason for the focus of the ENVI-Met software on one-day analysis is the complex nature of the microclimatic variables and the ability of the software to model detailed physical processes. The software simulates the interactions between different layers, such as the surface, vegetation, atmosphere and these change rapidly throughout the day. Therefore, simulations, which are usually limited to one day, provide more accurate results [48–50]. It is seen that the study area is quite comfortable in terms of climatic comfort as of 06:00. According to the measurements obtained at 09:00, roads and parking areas with hard surfaces are classified as very hot in terms of climatic comfort. However, the western parts of the buildings are characterized as warm and occasionally hot in terms of climatic comfort. As of 12:00, the climatic comfort value from the study area is very hot, while the western and northern parts of the buildings in the northwest and south have a hot scale. At 15:00, the hottest time of the day, the climatic comfort value of the study area is very hot. It is noteworthy that the eastern parts of the buildings have a hot value at 18:00 and reaches the warm scale at 21:00.

Figure 2. Study area and urban land use information.

Olgyay [51] stated that the temperature value for bioclimatic comfort is in the range of 21.0–27.5 °C, the relative humidity value is 30–65% and the wind speed is 5 m/s, which are used in bioclimatic evaluations [3].

3.1. Potential Temperature

In the study area, the lowest potential temperature value is at 06:00 and the highest is at 15:00. At 06:00, the potential temperature value has a minimum value of 20.20 °C in the eastern and northern sections of the buildings. At this time, minimum temperature values are observed in the northern and eastern parts of the study area. At 15:00, which is the hottest hour of the day, the potential temperature value reaches the highest level with 39.69 °C in the northern and eastern parts of the study area (Figure 3).

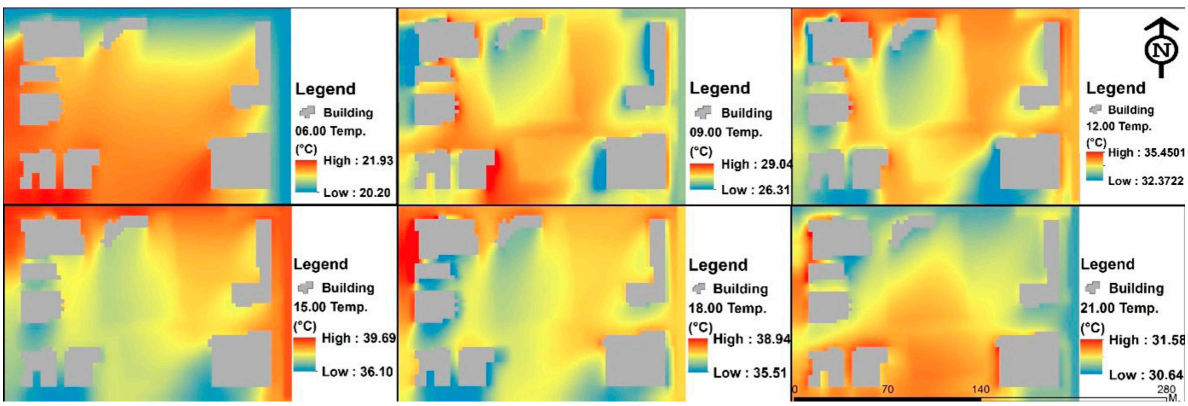

Figure 3. Temperature values of the study area in terms of thermal comfort.

In the potential temperature analysis, the relationships between surface materials and building orientation were examined in more detail to explain why certain areas reach higher temperatures. The analysis shows that hard surfaces like asphalt and concrete have a high heat capacity, which increases surface temperatures. These surfaces absorb solar radiation and store heat, which negatively impacts thermal comfort, especially during the hottest hours of the day. Additionally, the east and west facades of north–south-oriented buildings are exposed to intense sunlight throughout the day, leading to temperature increases in these areas. This situation highlights how building materials and orientation affect microclimatic conditions, emphasizing the importance of considering surface types and building orientation in urban planning and design. Reducing hard surfaces and positioning buildings to support thermal comfort emerge as key strategies for reducing heat retention and improving bioclimatic comfort in urban areas.

3.2. Relative Humidity

In the study area, the lowest relative humidity was at 15:00 and the highest was at 06:00. The relative humidity reached the highest value especially in the western and southwestern parts of the buildings at 6:00 a.m. The relative humidity was lowest in the northern and eastern parts of the buildings at 15:00 (Figure 4).

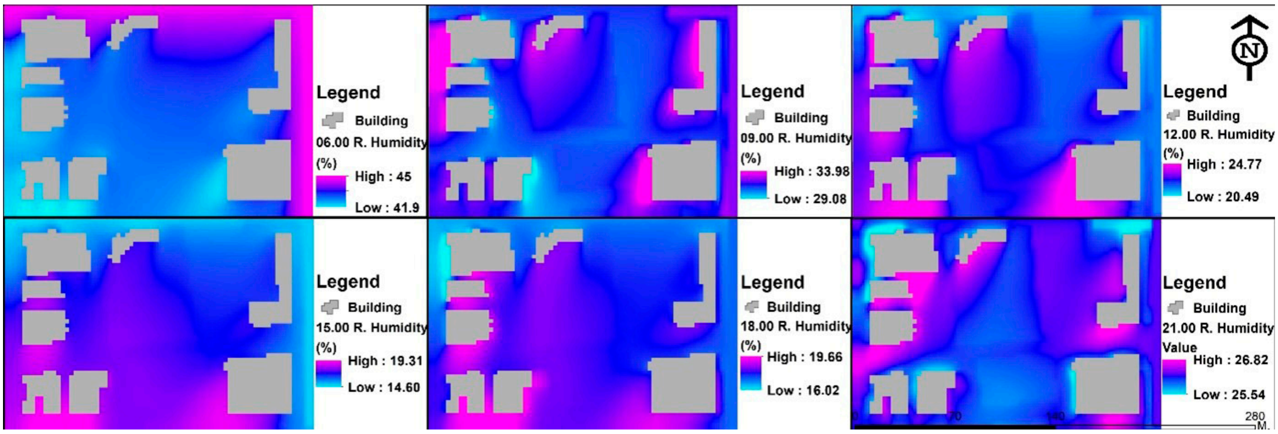

Figure 4. Relative humidity values of the study area in terms of thermal comfort.

The impact of relative humidity on thermal comfort is particularly notable in low-wind speed conditions, as these conditions reduce the body's ability to cool through evaporation, thereby increasing thermal discomfort. Conversely, the presence of wind can enhance evaporative cooling in high-humidity conditions, improving thermal comfort. The interaction between relative humidity and wind speed emerges as a critical factor influencing comfort levels in the study area, highlighting the importance of wind corridors and airflow in maintaining microclimatic comfort in urban spaces.

3.3. Wind

The prevailing wind direction in the study area as of 15 August 2023 is northeast. Since the buildings form a barrier at the edges of the buildings, the wind speed decreases and changes direction from time to time. Wind speed varies between 0–2.3 m/s in the study area. As stated by Olgyay [51], since the wind speed has a value below 5 m/s, it can be said that the wind does not affect thermal comfort much in the study area and has a very limited effect (Figure 5).

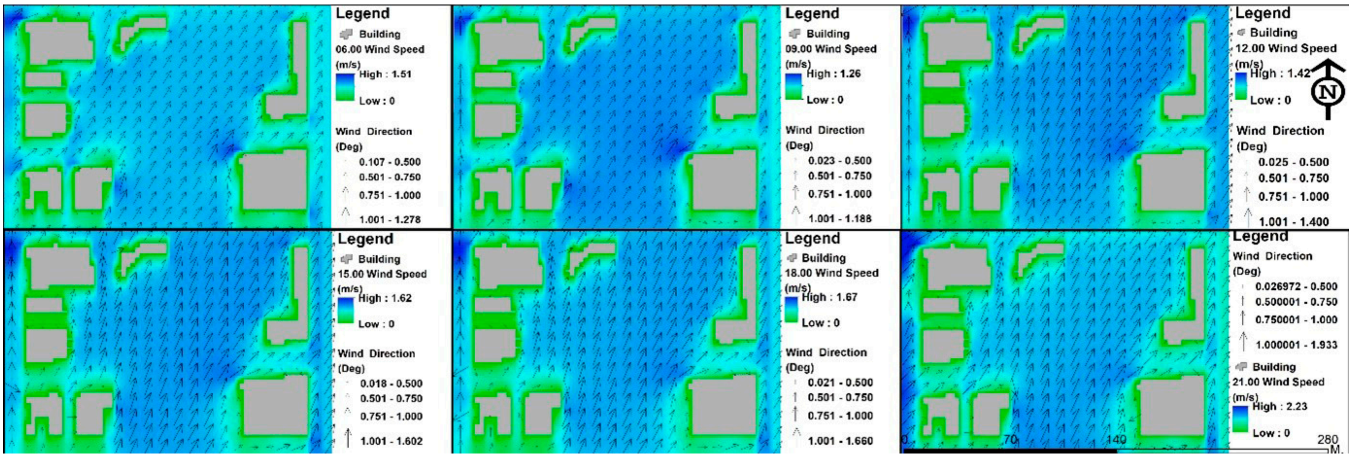

Figure 5. Wind characteristics of the study area in terms of thermal comfort.

3.4. PET Sensed Temperature

The Physiological Equivalent Temperature (PET) range was defined by [41] and the temperature range of 18–23 °C is considered comfortable [41]. From this point of view, it is seen that the working area is comfortable around 6:00 a.m., but bioclimatic comfort is low in all hours measured after 9:00 a.m. The time periods with the lowest bioclimatic comfort are 15:00 and 18:00. The bioclimatic comfort is relatively higher in the northern and eastern parts of the buildings and green areas at 15:00. It is understood that the eastern parts of the buildings and the shaded areas become relatively more comfortable due to the decrease in the sun angle at 18:00 (Figure 6).

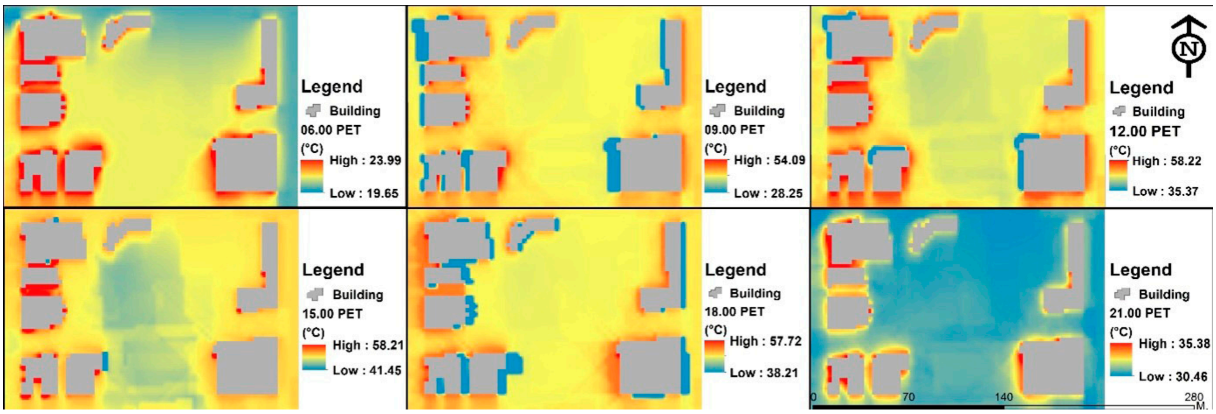

Figure 6. PET characteristics of the study area in terms of thermal comfort.

The PET values derived from this study provide crucial insights for urban planning in Burdur. By identifying areas with elevated PET values—indicating high thermal stress—planners can prioritize these locations for the incorporation of green spaces. Vegetated zones, particularly those with trees that provide substantial canopy cover, can be strategically designed to reduce PET values, thus enhancing thermal comfort. This targeted approach in green space optimization not only supports the creation of comfortable microclimates but also contributes to the broader goal of sustainable and climate-resilient urban development in Burdur.

3.5. Thermal Perception

Matzarakis et al. [41] consider places with temperatures in the range of 18–23 °C to be comfortable. In this respect, the study area has largely comfortable microclimatic characteristics, except for slightly warm areas on the sides of the buildings at 6:00 a.m. At 9:00 a.m., the perceived temperature on the western sides of the buildings is warm, the areas around the buildings are very hot and a narrow area is hot. The working area is largely characterized by being very hot, with a narrow area of hot values at 12:00 p.m. In the afternoon at 15:00, the entire study area is very hot. By 18:00, the eastern side of the buildings is hot and the western part of the buildings is very hot. The central parts, where the ground is devoid of vegetation and has hard features such as asphalt, concrete and parquet, retain a lot of heat and are, therefore, characterized by very hot (Figure 7).

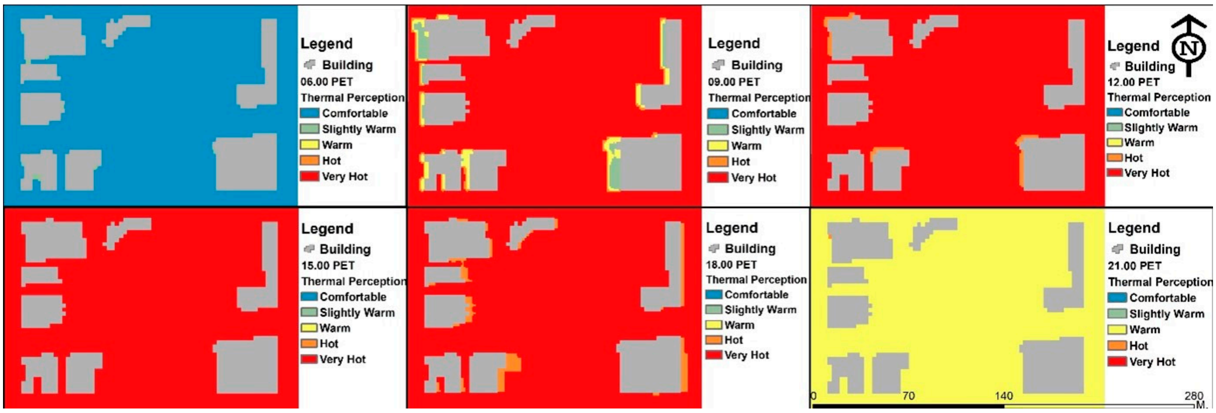

Figure 7. Thermal Perception characteristics of the study area in terms of thermal comfort.

Temperature increase in urban areas is seen as an important problem all over the world. Accordingly, there is an increase in research on temperature increase in cities. In our world where more than half of the population lives in cities, the necessity to create new settlement areas in urban areas with the ongoing migration causes the amount of area covered with hard ground to increase day by day. The coating of roads, buildings and open space surfaces in urban areas with concrete, asphalt, natural stone, etc., increases the surface temperature and leads to an increase in temperature in urban areas [20].

Due to increasing urbanization, natural areas are decreasing while ground coverings made of artificial materials such as asphalt and concrete are increasing. Such artificial paving materials have a high heat capacity, leading to a large accumulation of radiant energy on the surface. The irregularity of buildings as well as street systems prevents ventilation and leads to urban thermal environmental problems such as heat waves, heat islands and tropical nights, especially in summer [52]. In our study area, the lowest bioclimatic comfort is at 15:00 and the PET value is in the range of 41.45–58.21 °C at this time. The temperature value is quite high and uncomfortable in areas exposed to direct solar radiation on concrete floors. Comfortable areas in the study area are shaded areas and green areas. As a matter of fact, Jeong et al. [52] found that the bioclimatic comfort value in summer is low in areas with flooring materials such as asphalt, concrete and clay blocks, while areas shaded by green areas, buildings and trees have a relatively comfortable level.

The maximum value of PET in a green unshaded area is 35 °C, while in an area covered by an asphalt surface, it can exceed 58 °C. Green surfaces can contribute to the creation of an "ideal urban climate" by creating different microclimatic characteristics and diversity over short distances [53]. Ketterer and Matzarakis (2014) stated that the effect of vegetation reduces thermal stress in urban areas and has a positive effect on bioclimatic comfort [54]. The analysis of the study area is also consistent with the findings of [54]. Figure 5, which shows the PET value, shows that the PET value is relatively low at 15:00 in the area where Pinus pinea and Cedrus libani trees are located. This shows the potential of trees to increase bioclimatic comfort. This potential of trees is mainly determined by their geometry, crown structure and LAD (leaf area density, m^2/m^3) and depends on the blocking of direct solar radiation [48]. It is also noteworthy that the artificial shade created by buildings is more effective than vegetation. In the study area, it is understood that the eastern part of the building at 12:00 and the eastern part of the buildings in the study area at 15:00 are more comfortable than the western part. This is in line with the findings of [54,55].

Since urban areas are covered with asphalt and concrete, the temperature values increase in these areas. As a matter of fact, researchers have shown that in places where asphalt is used intensively, the temperature value reaches 50.98 °C on asphalt surfaces, 50.78 °C on andesite surfaces, 44.76 °C on bricks and 44.53 °C on concrete surfaces during the hottest hours of the day. In green areas, the temperature value is quite low. While it is 32.53 °C on surfaces covered with grass, the temperature created by the brick material in the tree shade can drop to 29.76 °C [3].

As shown in Figures 3 and 7, different surface types have a significant impact on PET (Physiological Equivalent Temperature) and thermal comfort. Figure 3 illustrates that hard surfaces (asphalt, concrete) in the study area retain more heat, thereby lowering thermal comfort levels. Higher temperature values are observed on these surfaces, particularly in the afternoon hours when thermal stress intensifies. In Figure 7, when evaluating the PET map, it is evident that green areas enhance thermal comfort, with tree-shaded areas significantly reducing PET values and improving bioclimatic comfort.

These findings demonstrate how the composition of urban surfaces affects microclimatic conditions, emphasizing the importance of surface types in urban heat island effects within Burdur's urban spaces. Hard surfaces like concrete and asphalt increase thermal stress, while vegetated areas lower PET values, thus improving thermal comfort. In this context, reducing hard surfaces and increasing green areas emerge as essential strategies for mitigating urban heat island effects and enhancing thermal comfort in cities like Burdur [56].

4. Conclusions

In this research, Physiological Equivalent Temperature (PET) and Thermal Perception were modeled by ENVI-Met and evaluated temporally and spatially by considering land use, potential temperature, relative humidity and wind parameters in the study area selected from Burdur city. Considering that more than half of the world's population lives in cities and the number of people living in urban areas will increase in the coming decades, the temperature and climatic comfort in urban areas becomes even more critical. In this context in the 33,665 m^2 study area, the climatic comfort of the urban area was determined with the current situation QGIS Geodata to ENVI-Met plug-in, based on data from six different time periods of 3 h intervals (06:00, 09:00, 12:00, 15:00, 18:00 and 21:00) for 15 August 2023.

In conclusion, it was determined that while the work area was comfortable around 6:00 in terms of Physiological Equivalent Temperature (PET) value, bioclimatic comfort was low in all hours measured after 9:00. The time periods with the lowest bioclimatic comfort are 15:00 and 18:00, respectively. As a matter of fact, at 6:00 a.m., the study area is largely comfortable, with only slightly warm areas on the sides of the buildings. From 12:00 onwards, the study area is largely characterized by being very hot, while at 15:00 in the afternoon, the entire study area is on a very hot scale. By 18:00, the eastern part of the buildings is hot and the western part of the buildings is very hot. In the central part of the study area, the ground is devoid of vegetation and consists of hard surfaces such as asphalt, concrete and parquet. These central areas are especially exposed to direct sunlight and retain a lot of heat and are, therefore, characterized by being very hot.

As a result, it is seen that green areas contribute to bioclimatic comfort by creating a cooling effect, especially the shaded parts that are more comfortable. It can be concluded that green areas (tree and grass) should have more space in urban areas and hard coating materials such as asphalt and concrete, which absorb a lot of heat and increase the felt temperature, should be avoided and limited as much as possible. At this point, it is considered very important for bioclimatic comfort, wildlife, clean air, livable and sustainable cities that local governments prioritize and design more green areas in landscape planning in urban land use.

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