Urbanization and Microclimate Change: A Case Study of Bukit Halimun, Luwuk

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Abstract

Urbanization is a process that occurs when the population in urban areas continues to rise, often accompanied by the development of infrastructure and other constructions within the urban scope. While urbanization brings various benefits such as economic growth and technological advancement, it also has negative impacts on the urban microclimate. These include the continuous reduction of green spaces leading to higher temperatures in the area and creating discomfort for humans, air pollution, declining air quality in urban environments, and potential health risks. Cities are expected to accommodate various activities of their residents, including housing, work, and recreation. With limited land available and a growing population, the demand for land increases. This situation inevitably leads to changes in land use within urban areas, where green spaces shrink over time. This study employs a deductive quantitative method with an evaluative approach, utilizing object modelling, simulation, and analysis through the Envi-MET software. This method is used to assess the impact of urbanization on microclimate changes, considering variables such as air temperature, wind speed, and relative humidity, which can affect outdoor thermal comfort levels. The research is focused on the Bukit Halimun Area, Luwuk City, Banggai Regency, Central Sulawesi. In 2007, the local government of Banggai Regency issued a policy for the Building and Environmental Planning for the Bukit Halimun area, covering a total planning area of 92 hectares. This area is intended for the development of office, residential, commercial, and educational zones.

Keywords: Urbanization, Microclimate, Urban Area, Bukit Halimun Luwuk, ENVI-met

I. INTRODUCTION

Urbanization is a process that occurs when the population in urban areas continues to rise, often accompanied by the development of infrastructure and other constructions within the urban scope. While urbanization brings various benefits such as economic growth and technological advancement, it also has negative impacts on the urban microclimate [1]. These include the continuous reduction of green spaces, leading to higher temperatures in the area and creating discomfort for humans, air pollution, declining air quality in urban environments, and potential health risks [2]. Urban areas as centers of activity have a high level of natural resource consumption, significantly contributing to environmental issues. From an environmental perspective, urban areas are often regarded as ecological concerns. The development of urban areas is closely linked to population growth influenced by both natural and non-natural factors [3]. Cities are expected to accommodate various activities of their residents, including housing, work, and recreation. With limited land available and a growing population, the demand for land increases. This situation inevitably leads to changes in land use within urban areas, where green spaces shrink over time. This condition has the potential to create environmental issues that disrupt air circulation patterns in urban areas, ultimately leading to significant temperature differences between the urban core and its surrounding suburbs [2, 4].

Urban microclimate is influenced by a combination of interconnected factors, particularly vegetation, urban surfaces, and urban geometry [5]. Vegetation plays a vital role in moderating urban temperatures by providing shade through tree canopies, which reduces the amount of solar radiation reaching ground surfaces [6]. In addition, vegetation contributes to evapotranspiration, a process that releases moisture into the atmosphere, thereby increasing humidity and creating a cooling effect. Conversely, urban areas characterized by extensive hard surfaces and limited vegetation tend to experience higher temperatures due to reduced shading and lower evapotranspiration rates [7]. Urban surfaces also have a significant impact on microclimatic conditions because different materials possess varying thermal properties. Light-colored surfaces generally reflect a greater proportion of incoming solar radiation, helping to reduce heat accumulation, whereas darker materials, such as asphalt and certain roofing types, absorb and retain more heat, intensifying the urban heat island effect. As urban environments become increasingly dominated by impervious surfaces rather than natural land covers, including green spaces and water bodies, their capacity to regulate temperature diminishes [8]. Furthermore, urban geometry, which encompasses the size, height, orientation, and spacing of buildings, substantially affects local climatic conditions by influencing airflow, solar radiation exposure, and heat exchange processes. Dense building configurations can restrict ventilation, alter wind circulation patterns, and create urban canyons where heat is absorbed, reflected, and trapped between structures. These combined effects reduce heat dissipation and contribute to elevated air and surface temperatures, making urban geometry a critical determinant of urban microclimate dynamics [9].

The location chosen for this study is the Bukit Halimun Area, Luwuk, Banggai Regency, Central Sulawesi. According to data from the Central Statistics Agency of Banggai Regency in 2020, the population of Banggai Regency reached 362,275 people. The population growth rate from 2010 to 2022 is 1.10%, with population density concentrated in the South Luwuk Subdistrict, which has 200 people per square kilometer [10]. Based on projection calculations, the population of South Luwuk Subdistrict is estimated to reach 25,779 people by 2030 as in the following table 1.

Table 1. Population Projection of South Luwuk Sub-district

Subdistrict	Ratio	Total Population		
		2016	2023	2030
South Luwuk	0,015	22.917	23.270	25.779
Population Incrase			**+353**	**+2.509**

In 2007 the local government of Banggai Regency issued the Building and Environmental Planning policy for the Bukit Halimun Area with a total planning area of 92 hectares. This area is planned for the development of office, residential, commercial, and educational zones. Geographically, Bukit Halimun is located in a hilly region, with elevations ranging from 75 to 165 meters above sea level. The land slope in this area varies from 5% to 15%, with a dominant hilly, relief-based terrain. In the development plan for Bukit Halimun, the Building Coverage Ratio (BCR) is set between 30% and 40%, while the Floor Area Ratio (FAR) is determined to range from 0.2 to 1.2. [11, 12]. Indeed, this study aims to investigate the influence of key urban attributes, including urban geometry, vegetation, and urban surface on the microclimatic characteristics of the study area. Furthermore, it evaluates the microclimatic performance of the Bukit Halimun New Urban Area based on the implementation of the existing development plan and proposes adaptive urban design strategies to mitigate future microclimate change.

II. METHOD

This study employs a deductive quantitative method with an evaluative approach, utilizing object modelling, simulation, and analysis through the Envi-MET software. This method is used to assess the impact of urbanization on microclimate changes, considering variables such as air temperature, wind speed, and relative humidity, which can affect outdoor thermal comfort levels. In addition, this method is also used to examine the factors that cause microclimate changes in the area. Envi-met is a software used to simulate microclimate conditions, with the capability to integrate various natural elements such as air temperature, wind, radiation, vegetation, soil, and pollutants within a given area. This software can calculate the microclimate cycle over a period of 24 to 48 hours by utilizing the basic principles of fluid dynamics and thermodynamics [13]. The Envi-met program can also analyze the impact of vegetation on the area's microclimate, as well as the energy exchange processes on paved surfaces, walls, and building roofs [14].

A. Research Stage

The research methodology was conducted through seven sequential stages. The first stage involved a comprehensive literature review to establish the theoretical and conceptual foundation of the study. The second stage focused on data collection, including primary and secondary data related to the physical characteristics, environmental conditions, and spatial attributes of the study area. In the third stage, urban attributes were analyzed to identify the existing urban form, land use, vegetation, building configuration, and other factors influencing the microclimate. The fourth stage consisted of conducting microclimate simulations using ENVI-met to evaluate the thermal performance of the existing urban environment under current conditions. The fifth stage involved assessing the simulation results to evaluate the effectiveness of the existing urban development in terms of thermal comfort and environmental performance. Based on these findings, the sixth stage formulated adaptive urban design strategies aimed at enhancing outdoor thermal comfort and climate resilience. Finally, the seventh stage synthesized the results into a set of urban design guidelines to support sustainable and climate-responsive urban development as seen in the following Figure 1.

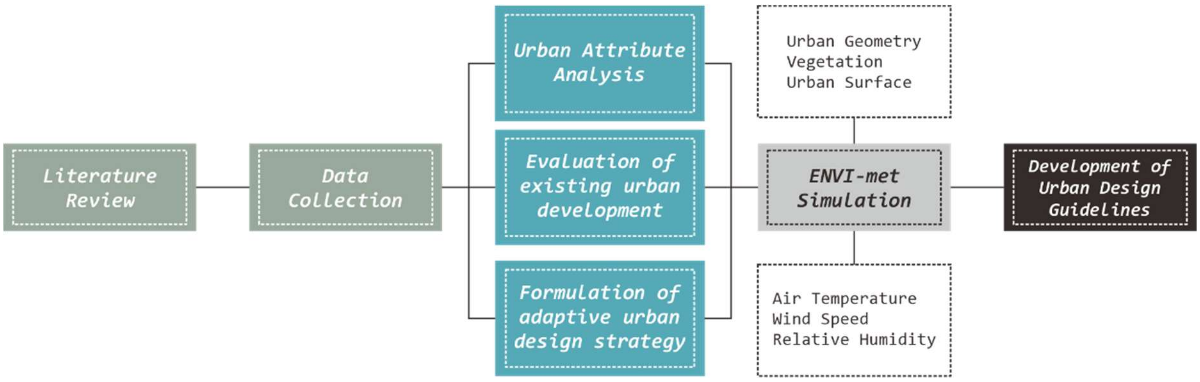

Figure 1. Research Stage

B. Data Collecting Techniques

This study uses two sources of data, primary and secondary data. Primary data includes information obtained directly from the research site through observation and area mapping. Meanwhile, secondary data consists of information gathered from relevant agencies, such as climate data for Luwuk City from the BMKG Luwuk and the Building and Environmental Planning of the Bukit Halimun area from the 2007 report by the PUPR Department of Banggai Regency.

C. Data Processing Method

The microclimate simulation in this study was conducted using ENVI-met software, which requires several input datasets, including pavement characteristics, the geometric configuration of the study area, and vegetation data. The simulation process consisted of six sequential stages. First, the preparation stage involved defining the study location, setting the elevation, and establishing the simulation grid and boundary conditions using the ENVI-space module to ensure accurate representation of the actual site. Second, the digitization stage was carried out by modelling the existing physical environment, including buildings, roads, pedestrian pathways, and vegetation, within the ENVI-space environment. Third, the configuration stage involved specifying the simulation period, duration, and local meteorological parameters, such as air temperature, wind speed, and relative humidity, through the ENVI-guide module. After all, input data had been completed, the simulation stage was performed using the ENVI-core module to generate the microclimate conditions of the study area. Subsequently, the calculation stage employed the Biomet module to assess outdoor thermal comfort based on the Predicted Mean Vote (PMV) index. Finally, the data processing stage utilized the Leonardo module to visualize the simulation outputs as pedestrian-scale thermal maps and export the results into Microsoft Excel format for further analysis.

III. Results and Discussion

Rapid urbanization has substantially transformed the spatial and environmental characteristics of cities, often resulting in inefficient land use and uncontrolled urban expansion, commonly known as urban sprawl [15]. As the demand for residential, commercial, industrial, and transportation infrastructure continues to increase, natural landscapes and green open spaces are progressively converted into built-up areas dominated by impervious surfaces such as roads, buildings, and pavements. This transformation not only degrades environmental quality but also weakens the ecological functions of urban areas by reducing vegetation cover, limiting evapotranspiration, and increasing heat absorption and storage. Consequently, these changes contribute to alterations in the urban microclimate, including higher air and surface temperatures, reduced thermal comfort, and the intensification of the urban heat island effect. Since urban microclimate is shaped by the interaction of multiple physical and environmental factors, understanding the influence of urban development characteristics is essential for promoting sustainable and climate-resilient cities [2, 16, 17]. Therefore, this study investigates the effects of several key urban factors, including development density, the availability of green open spaces, and the characteristics of pavement materials, on microclimate changes in urban areas [5, 18], with the aim of providing empirical evidence to support more sustainable urban planning and environmental management.

A. Effect of Density on Microclimate Change

One of the factors that can impact the microclimate changes in an area is building density. Several density factors affecting microclimate changes include the Building Coverage Ratio (BCR), Floor Area Ratio (FAR), Green Base Coefficient (GBC), and building height [19]. To assess the extent of the influence of density on microclimate changes in an area, a microclimate simulation was conducted using Envi-met software. The simulation was carried out on May 1, 2024, over a 24-hour period and utilizing meteorological data from the Syukuran Aminuddin Amir Airport weather station in Luwuk, including air temperature, wind speed, and relative humidity data from May 2024. The purpose of this simulation was to test areas with a BCR ranging from 30% to 50%, as well as areas with a BCR of 70%, and to analyze the impact of the height-to-width ratio (H/W) on the microclimate changes in the area.

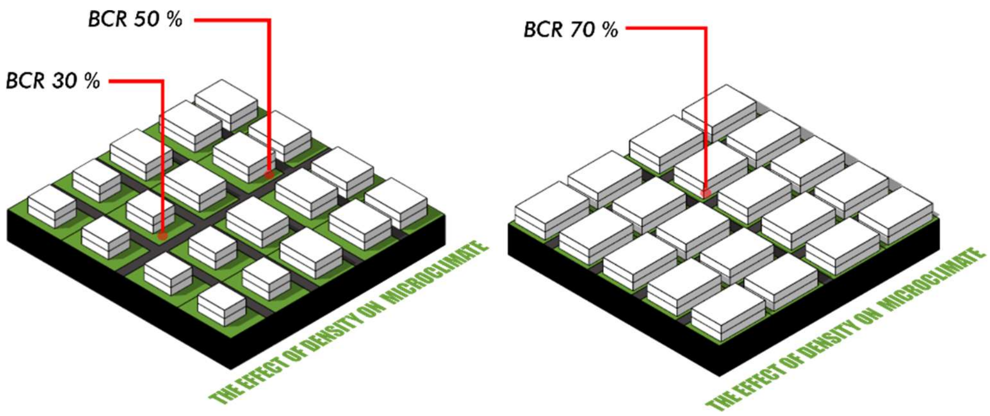

Figure 2. Testing the Effect of Density on Microclimate Changes

At first glance, the thermal map below does not appear to show a significant difference. However, upon closer inspection, it becomes evident that canyon-like urban areas with a Building Coverage Ratio (BCR) of 70% tend to exhibit slightly higher air temperatures compared to zones with a BCR of 30–50%. In the 70% BCR area, the minimum temperature recorded is 31.37°C, while the maximum reaches 34.44°C. These values are marginally higher than those in the 30–50% BCR zones, which show a minimum temperature of 31.79°C and a maximum of 34.22°C. High building density combined with narrow spacing between structures contributes to heat accumulation, allowing solar radiation to be trapped within the urban canyon. This effect leads to elevated ambient temperatures in these denser built environments. In addition, within areas with a Building Coverage Ratio (BCR) of

70%, there are zones that exhibit cooler air temperatures compared to those with a BCR of 30 to 50%. This condition is influenced by relatively strong wind flows coming from the west, which accelerate further as they pass through areas with canyon-like urban morphology.

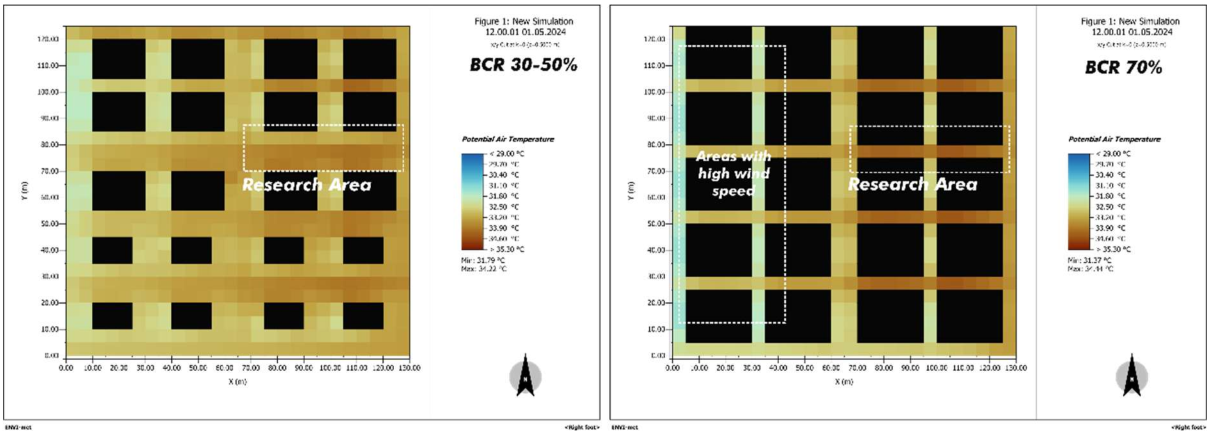

Figure 3. Thermal Map of Density Against Microclimate Change

Based on the graph below, it shows that areas with a building coverage ratio (BCR) of 70% during the day tend to experience a slight increase in air temperature compared to areas with a BCR of 30% to 50%. The most significant temperature difference occurs at noon, at 12:00 PM, with a temperature difference of 1.27°C. This indicates that as the density of an area increases, it results in a rise in the air temperature within that area.

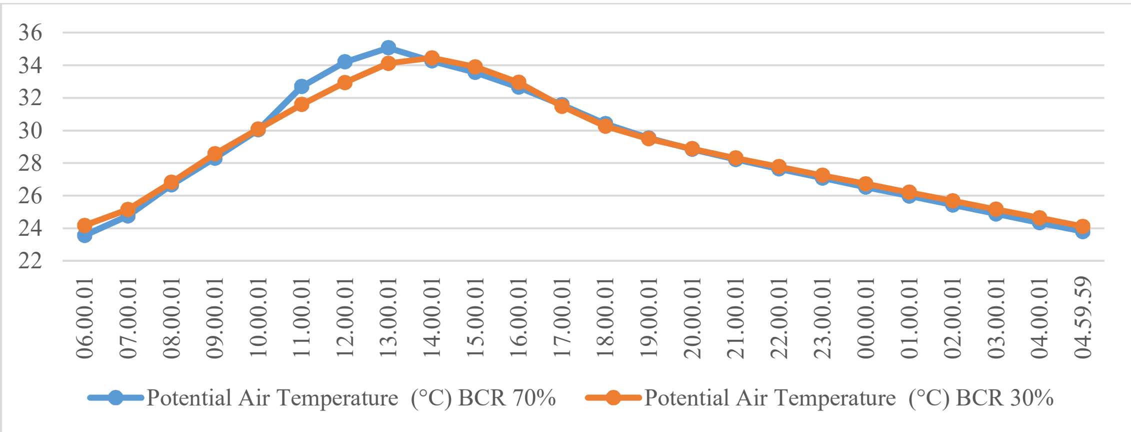

Figure 4. Graphic of the Effetc of Density on Air Temperature

The wind speed graph below indicates that the density of an area affects wind speed. Areas with a 70% BCR tend to have higher wind speeds compared to areas with a BCR of 30-50%. Conversely, areas with a BCR of 30-50% provide a more comfortable wind flow for the users of the space. This shows that in areas with closely spaced buildings the wind tends to move faster which can lead to discomfort for the occupants.

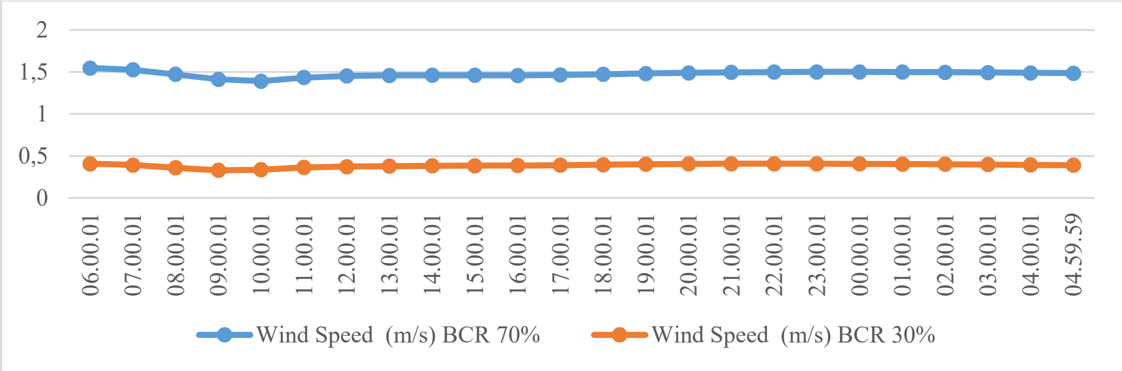

Figure 5. Graphic of the Effetc of Density on Wind Speed

B. Effect of Green Area on Microclimate Change

The presence of green open spaces and vegetation in urban areas is considered crucial as it influences the urban microclimate. In addition to providing shade in urban areas, the ability of vegetation to absorb much of the solar radiation and convert it into water vapor through transpiration has an impact on reducing the air temperature of the area [17]. The sample urban area shown in the image below has green space added in the center to test the extent to which green open spaces and vegetation in an urban area affect microclimate changes.

Based on the thermal map simulation below, it is evident that the presence of green open spaces and vegetation plays a crucial role in reducing the air temperature of an area. Additionally, the green spaces and vegetation distributed throughout the urban area can help reduce wind speed, creating a more comfortable sensation for urban space users. Looking at the thermal map of an area without green space (Figure 1.3, number 1), at 12:00 PM, the minimum air temperature in the area is 31.79°C, with a maximum temperature of 34.22°C. On the other, in the area with green space (Figure 1.6), there is a noticeable drop in air temperature. At noon, the minimum air temperature in the area is 29.65°C, with a maximum of 33.85°C.

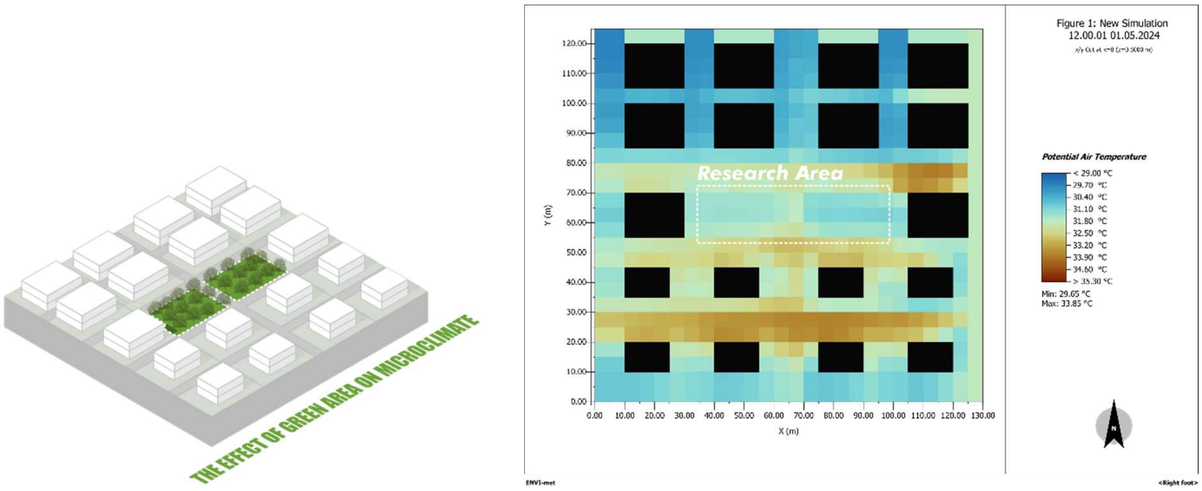

Figure 6. Testing the Effect of Green Area on Microclimate Changes

Based on the graph below, it is evident that the presence of green spaces and vegetation significantly impacts the reduction of air temperature and wind speed in urban areas. This demonstrates that in the design of urban areas, the existence of both public and private green open spaces, with vegetation distributed throughout the area, plays a vital role in lowering air temperature and wind speed.

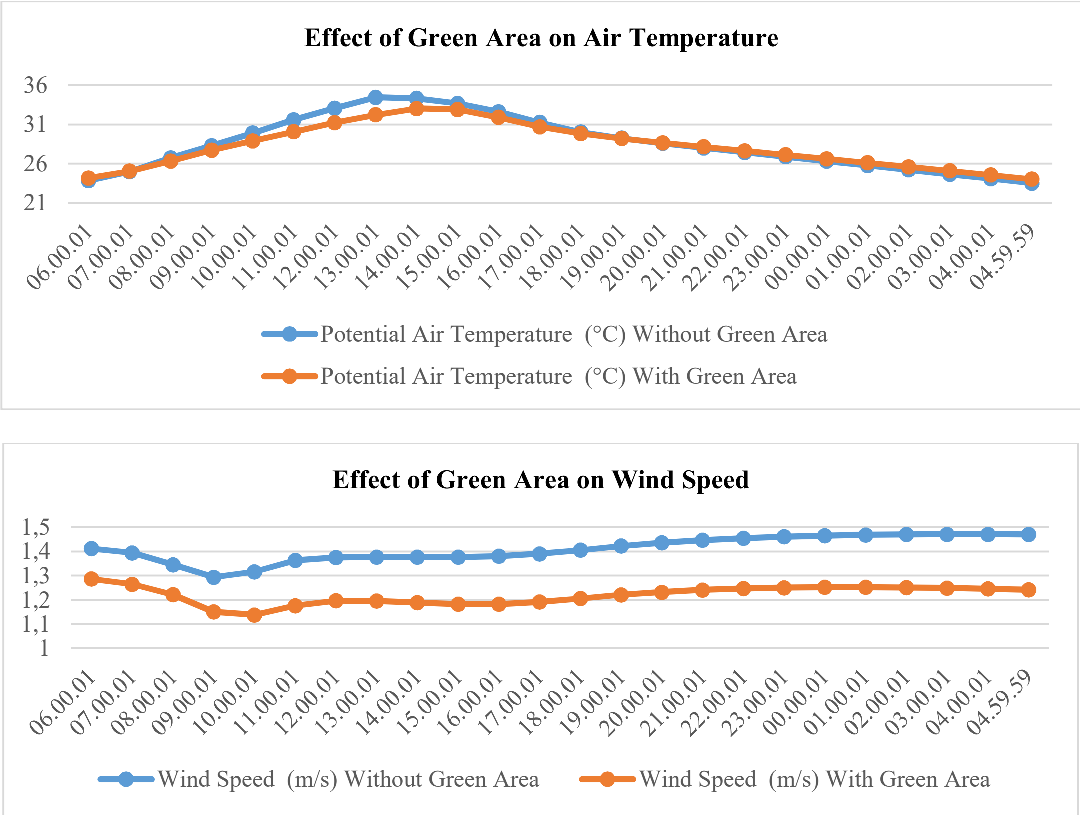

Figure 7. Graphic of the Effetc of Green Area on Air Temperature and Wind Speed

In addition to influencing air temperature and wind speed, the presence of green open spaces and vegetation in urban areas can also impact the relative humidity levels of a region. Vegetation has the ability to release water vapor through its leaves into the atmosphere, which results in increased humidity within the area.

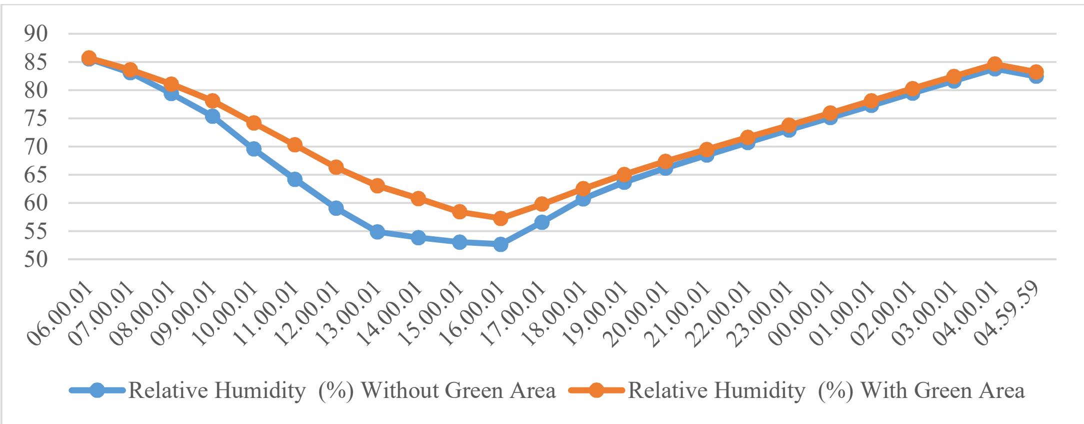

Figure 8. Graphic of the Effetc of Green Area on Relative Humidity

C. Effect of Surface Materials on Microclimate Change

Urban surface materials have an impact on the microclimate of urban areas. Surface materials with light colors and reflective properties can reflect solar radiation back into the atmosphere. On the other hand, surface materials with dark colors tend to absorb more solar radiation, making the area hotter [20]. In the sample urban area below (Figure 1.9), all paving materials were changed from asphalt to concrete paving blocks, with the aim of testing the influence of urban surface materials on the microclimate of the area.

The simulation results indicate that the surface materials of an area affect the reduction of the area's air temperature. The concrete paving material in the area reflects more solar radiation preventing heat from being trapped within the area. As seen in the thermal map below (Figure 1.9), the minimum air temperature at noon is 29.11°C, with a maximum of 32.89°C. This shows a reduction in the air temperature of the area compared to the temperature in an area with asphalt materials (Figure 1.6), where the minimum temperature is 29.65°C and the maximum is 33.85°C. This suggests that the use of light-colored paving materials can significantly impact the microclimate of the area.

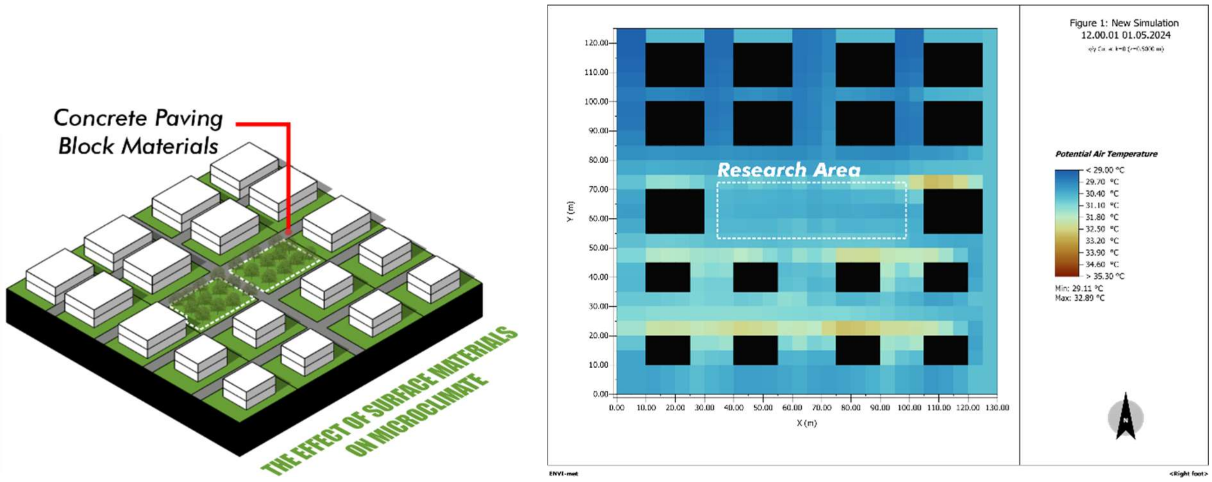

Figure 9. Testing the Effect of Surface Materials on Microclimate Changes

As shown in the graph below (Figure 2.1), there is a significant decrease in air temperature, with a minimum value of 0.001°C and a maximum value reaching 2.97°C, occurring at 1:00 PM. However, during the night, from 8:00 PM to 2:00 AM, the area experiences an increase in air temperature, with the maximum value reaching 0.081°C.

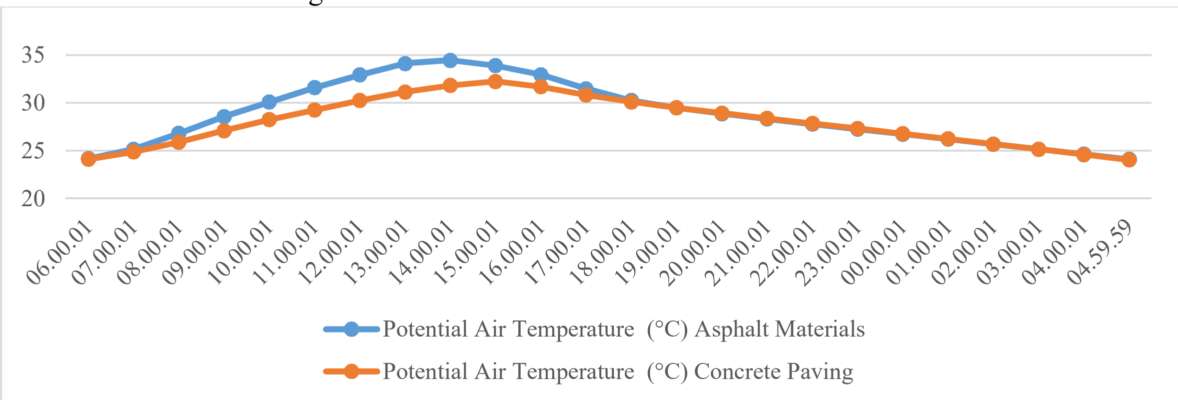

Figure 10. Graphic of the Effetc of Surface Materials on Relative Humidity

D. Microclimate Conditions of the New Urban Area of Bukit Halimun

The simulation area is focused on Block A, with a total area of 17.02 hectares. This is due to the fact that initial development has already been observed in this area within the new Bukit Halimun urban development. Currently, Block A has a built-up area percentage of 9%, primarily used for office functions, while the remaining 91% consists of green spaces. The microclimate simulation in the Bukit Halimun area is conducted using Envi-met software, with the simulation date set for May 1, 2024, over a 24-hour period. The simulation in this study uses climate data from the Syukuran Aminuddin Amir Luwuk Airport meteorological station, including air temperature and relative humidity data from May 2024.

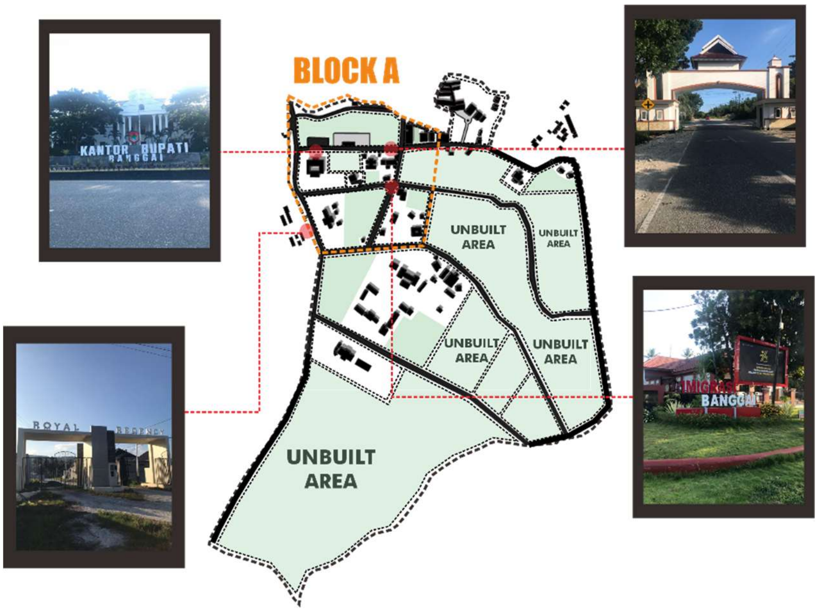

Figure 11. Research Area of the New Urban Area of Bukit Halimun

Based on the thermal map from the simulation below, the new urban area of Bukit Halimun experiences relatively high air temperatures with a minimum temperature of 29.74°C and a maximum temperature of 31.77°C. According to the SNI 03-6572-2001 in Table 2 [21, p. 11], the air temperature conditions at 12:00 PM in this area fall within the threshold for a hot sensation. The wind speed conditions at 12:00 PM in several areas of the new urban area Bukit Halimun are relatively high. The minimum wind speed in the area ranges from 0.37 m/s, with a maximum of 1.96 m/s. Based on the wind speed standards for thermal comfort in Table 3, the wind speed in some areas of Bukit Halimun is still considered comfortable. However, in certain areas the wind speed is classified as uncomfortable for space users.

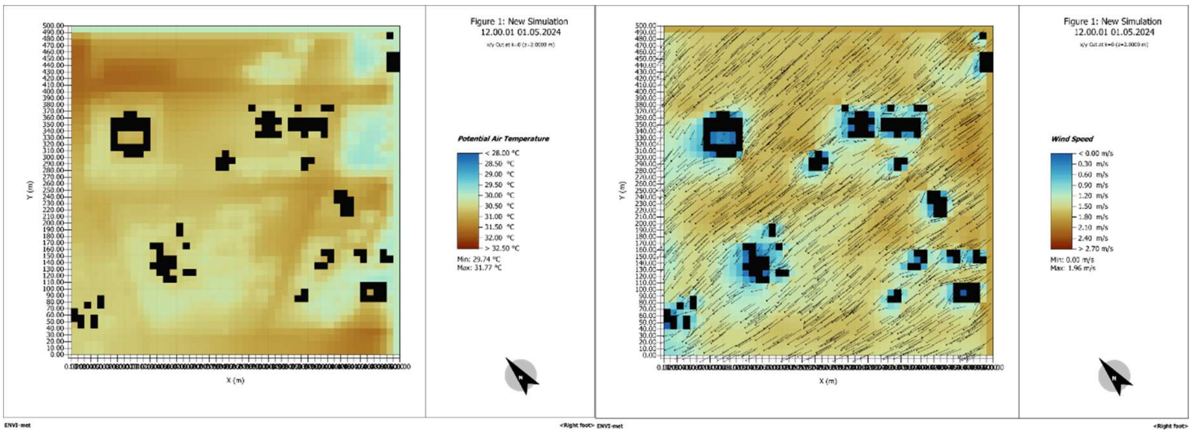

Figure 12. Air Temperature and Wind Speed Simulation Result in Bukit Halimun at 12:00 PM

E. Microclimate Mitigation Strategies for the Bukit Halimun New Urban Area

The design outcomes for the new urban area of Bukit Halimun incorporate several strategies to mitigate the impact of microclimate changes. These strategies include creating ample public and private green spaces distributed across the entire Block A area, regulating building heights and spacing with an H/W ratio of 5:5 to prevent the formation of urban canyons that could affect the area's microclimate, and selecting light-colored paving materials (for buildings, streets, and pedestrian ways) to minimize the absorption of solar radiation which could otherwise lead to an increase in the area's air temperature.

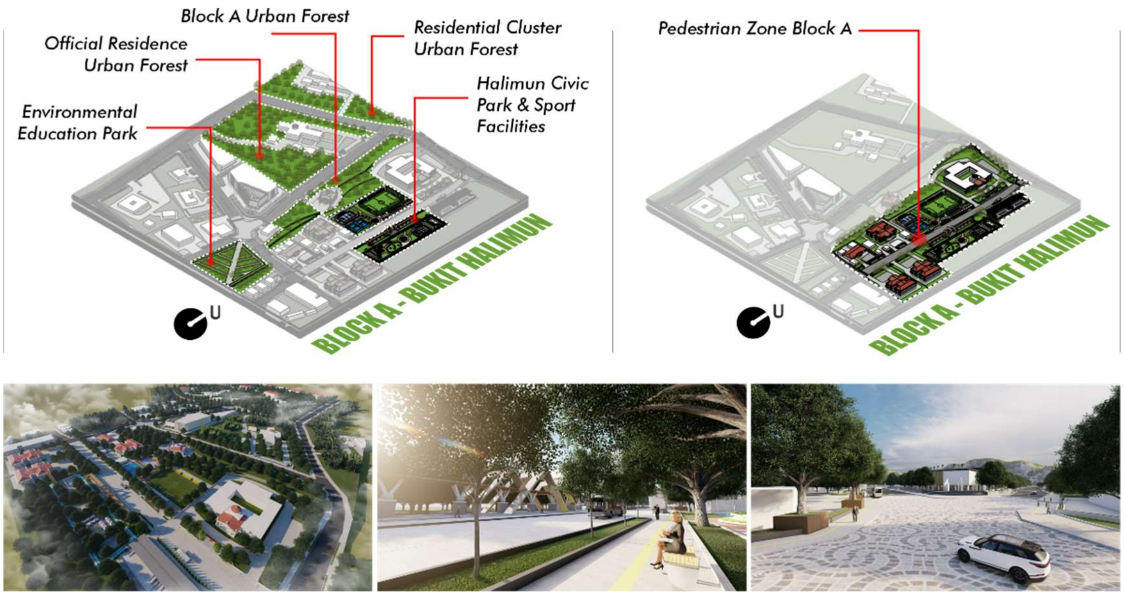

Figure 13. Visualization of the Design Result for Block A, Bukit Halimun Area

The design outcomes for Block A of the Bukit Halimun area show a decrease in air temperature compared to the previous conditions (Figure 2.3). The minimum air temperature at 12:00 PM drops to 28.71°C, and the maximum temperature decreases to 32.34°C. This result is attributed to the design strategy, which includes the creation of abundant green spaces and vegetation spread throughout the area, as well as the use of light-colored materials applied to pedestrian ways and road surfaces in the pedestrian zone of Block A. Additionally, wind speed in the Block A area has decreased significantly. Based on the wind speed thermal map (Figure 2.5), the overall design shows an increase in areas with comfortable wind speeds compared to the existing wind speed thermal map of the area (Figure 2.3) which typically has higher wind speeds. The minimum wind speed in the area is 0.20 m/s and the maximum is 2.48 m/s. This decrease in wind speed is attributed to the design of the area which incorporates a variety of scattered vegetation that acts as a natural wind barrier creating a more comfortable wind flow experience.

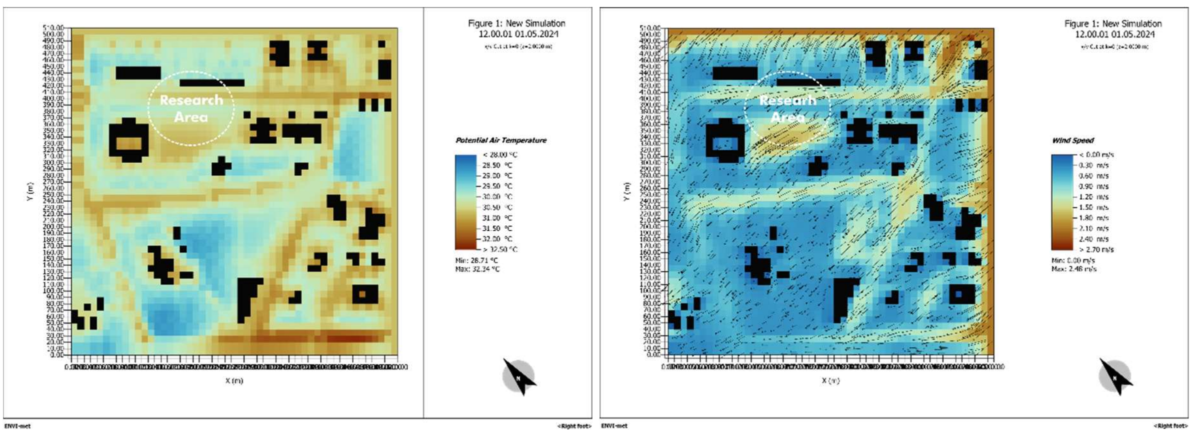

Figure 14. Simulation of Block A Design on Air Temperature and Wind Speed at 12:00 PM

Based on the temperature comparison graph below, the Bukit Halimun area experiences a maximum temperature decrease of 2.19°C occurring at 16:00 PM. Meanwhile, the minimum temperature decrease takes place at 6:00 AM with a reduction of 0.78°C.

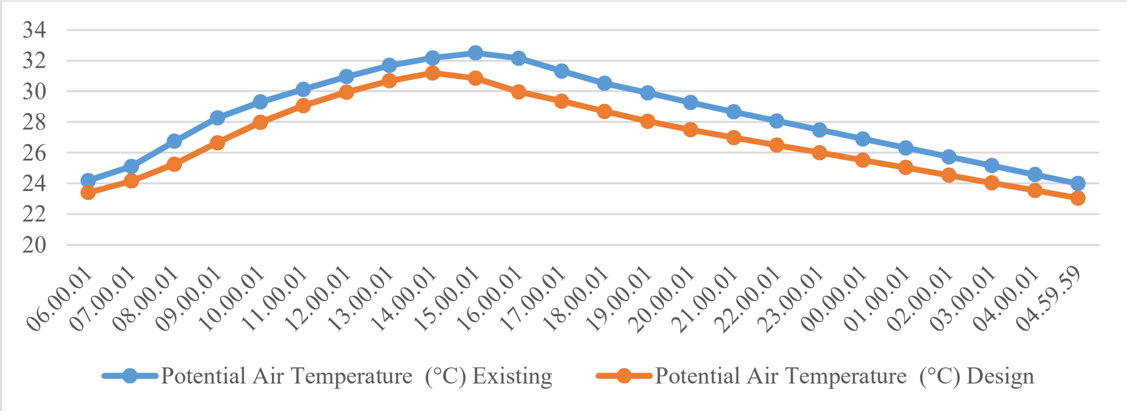

Figure 15. Comparison Graph of Existing Air Temperature and Design Result Wind Speed

Table 2. Classification of Thermal Comfort in Tropical Regions

Effective Temperature (ET)	Description
20,5 – 22,8 °C	Comfortably Cool
22,8 – 25,8 °C	Optimal Comfort
25,8 – 27,1 °C	Warm and Comfortable
31 °C	Threshold Hot

Source : SNI 03-6572-2001

Based on the wind speed comparison graph below, there is a significant decrease in wind speed, ranging from 0.92 m/s to a maximum reduction of 1,31 m/s. "The wind speed conditions in the Bukit Halimun area have become more comfortable for space users."

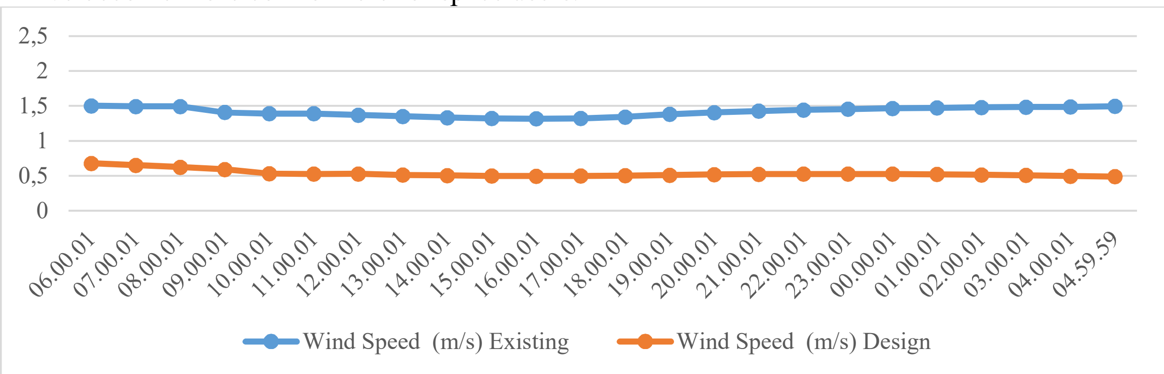

Figure 16. Comparison Graph of Existing Wind Speed and Design Result Wind Speed

Table 3. Wind Speed Classification and Thermal Comfort

Wind Speed (m/s)	Description
<0.25 (m/s)	Not Perceptible
0.25 – 0.5 (m/s)	Most Comfortable
0.5 – 1 (m/s)	Still Comfortable, Airflow is noticeable
1 – 1.5 (m/s)	Maximum Comfortable Speed
1.5 – 2 (m/s)	Uncomfortable, Windy
>2 (m/s)	Impactful on Occupant Health

Source : Heinz Frick, 2008 [22]

IV. Conclusion

The results of this study confirm that key urban attributes, namely urban geometry, vegetation, and land cover materials as identified in previous research, significantly influence the microclimatic characteristics of urban areas. These findings suggest that these attributes can be used as fundamental design parameters for developing climate-responsive urban design guidelines to mitigate future microclimate change in urban environments. The study area, namely the Bukit Halimun Area has been designated by the Banggai Regency Government as a planned new urban development area. Based on the existing site conditions, only approximately 5% of the total 92 Ha planned area has been developed, while the remaining 95% is still dominated by natural green open space. This condition represents one of the limitations of the present study, as the analysis is confined to the area where the initial phase of development has been completed. Nevertheless, the findings of this study are expected to serve as a valuable reference for the Banggai Regency Government in guiding the continued development of the Bukit Halimun New Urban Area through the implementation of climate-responsive urban design strategies, thereby mitigating future microclimate change.

To enhance the urban microclimate and promote environmental sustainability, several planning strategies should be considered. First, public green open spaces should be equitably distributed throughout the urban area, with a minimum allocation of 30% of the total planned area, in accordance with the regulations of the Indonesian Ministry of Public Works. For a planning area of 92 ha, this requirement corresponds to at least 27.6 ha of green open space. In addition to providing recreational opportunities and supporting social activities, well-distributed green spaces play a crucial role in regulating the urban microclimate by reducing heat accumulation, lowering ambient air temperatures, increasing evapotranspiration, and improving outdoor thermal comfort. Furthermore, both public and private green spaces, including trees and other vegetation, are essential for enhancing urban environmental quality, as they contribute to moderating air temperature, improving humidity conditions, reducing wind intensity, and mitigating the urban heat island effect. Urban form should also be carefully managed through appropriate building height and spacing regulations, with an H/W ratio of 5:5 to maintain adequate solar access and natural ventilation while minimizing excessive heat retention. Excessively narrow spacing between tall buildings creates urban canyons that restrict airflow, alter wind circulation, and trap solar radiation, thereby increasing local temperatures and reducing thermal comfort. Finally, the use of concrete paving blocks for pedestrian walkways and selected road surfaces is recommended to reduce excessive solar heat absorption by urban materials. Compared with conventional impervious paving, concrete paving blocks can help moderate surface temperatures, reduce heat storage, and improve the overall thermal performance of urban spaces, thereby contributing to a more comfortable, resilient, and climate-responsive urban environment.

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