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Microclimate Optimization for Public Open Spaces Using Envi-Met: a Case Study of Simpang Lima Pendopo

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ABSTRACT
This study analyzes the microclimate conditions of the Simpang Lima Pendopo area and evaluates the effectiveness of three levels of design intervention—20%, 40%, and 60% optimization—in improving the thermal comfort of public open spaces. Simulations using ENVI-met were conducted at 1:00 PM, 3:00 PM, and 5:00 PM to assess air temperature, relative humidity, wind speed, and PMV values. The results indicate that the existing conditions are still influenced by the dominance of hard pavement, minimal vegetation, and limited ventilation, resulting in high thermal discomfort. The 20% intervention has limited local impact, while the 40% scenario begins to improve heat distribution and comfort in pedestrian paths. The 60% scenario proved to be the most effective with a temperature decrease of 3–4°C, stable humidity, improved micro-ventilation, and PMV reaching the "warm–comfortable" category. The combination of three layers of vegetation, reflective-permeable materials, and water elements proved to be able to reduce heat, reduce hotspots, and create even thermal comfort. These findings confirm that large-scale vegetation-based interventions and surface management are effective strategies for improving microclimate quality in tropical urban areas.

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INTRODUCTION

Penukal Abab Lematang Ilir (PALI) Regency, established in 2013 as a division of Muara Enim Regency, has developed rapidly thanks to the strength of the coal mining, palm oil, and rubber plantation sectors, which are its main economic drivers. Located on a strategic route in South Sumatra, PALI plays a crucial role in connecting cross-regional economic flows through mining, trade, and inter-regional mobility. Population growth, which reached approximately 209,771 people in 2023, reflects the increasing intensity of urbanization and industrial activity, giving rise to new areas that serve as service and trade centers. Among these areas, Simpang Lima Pendopo stands out as the most prominent, serving as a mobility hub and the center of the regency's social and economic activities.

Simpang Lima Pendopo is located at the intersection of five main roads connecting Palembang, Prabumulih, Muara Enim, Musi Rawas, and Lubuklinggau, and is connected to the provinces of Bengkulu and Jambi. Its strategic location has encouraged the growth of this area as a distribution route for goods and services between regions, which has subsequently transformed it into a new urban node with a variety of activities ranging from trade and transportation to social and cultural functions. The strategic map of PALI Regency shows that this area, located in Talang Ubi District, is the center of the regency's activities and determines the direction of urban growth. The physical expansion of the Pendopo area is increasingly accompanied by increased activity in the mining, plantation, and transportation sectors, ultimately increasing the need for adequate public open space.

However, this rapid development presents serious challenges to the quality of urban space. Increasing vehicle volumes, the growth of commercial buildings, and the reduction of green areas have resulted in a decline in thermal comfort and the quality of open space. The combination of the dominance of hard surfaces, the lack of shade-providing vegetation, and rising ground temperatures demonstrates an imbalance between physical development and ecological sustainability. Simpang Lima Pendopo, as a major transportation node, faces increasing microclimate pressures, which, if not properly managed, could diminish the social, recreational, and ecological functions of this public space. The limited availability of comfortable and safe open space can diminish the quality of life for residents who depend on this area for gathering and activities.

From a sustainable urban design perspective, thermal comfort is a fundamental aspect that cannot be ignored. Oke (1987) explains that the thermal conditions of outdoor spaces are determined by the interaction of air temperature, humidity, wind speed, and solar radiation, which influence the surface energy balance. Givoni (1998) and Gehl (2013) emphasize that thermally comfortable outdoor spaces encourage social activity, while hot and poorly shaded spaces reduce the quality of social interaction. The Urban Heat Island (UHI) phenomenon, which frequently occurs in activity centers, including Simpang Lima Pendopo, is evidence of the decline in thermal quality due to the high density of hard surfaces and the reduction of vegetation and water resources. Oke (1987) emphasized that these conditions worsen thermal comfort, especially in areas with high solar radiation intake, as is the case in the PALI Regency activity center.

To address this issue, integrating the principles of sustainability and resilience is crucial in the design of public open spaces. Vegetation is a vital element because it can provide shade and reduce temperatures through evapotranspiration, as explained by McPherson et al. (1997). The right surface material can reduce excess heat absorption as stated by Santamouris (2014), while the water element provides a natural cooling effect through evaporative cooling according to Shashua-Bar & Hoffman (2000) and Bowler et al. (2010). A balanced combination of these three elements is needed to produce a more stable, comfortable, and environmentally friendly microclimate.

This study uses the ENVI-MET simulation tool developed by Bruse & Fleer (1998) to analyze the interactions of vegetation, materials, wind, and solar radiation at the microscale. Through this simulation, various design scenarios can be tested to evaluate changes in air temperature, humidity, wind speed, and the Predicted Mean Vote (PMV) value developed by Fanger (1970) as a subjective indicator of thermal comfort. This study applies stepwise optimization scenarios of 20%, 40%, and 60% of the existing conditions to identify optimal thermal efficiency points, as suggested by Oke (1987), Shashua-Bar & Hoffman (2000), and

Ng et al. (2012). This stepwise approach provides a measurable understanding of how changes in physical elements affect the area's microclimate.

Therefore, this study aims to analyze and optimize the thermal comfort of public open spaces at Simpang Lima Pendopo through ENVI-MET-based simulations. The results are expected to provide the basis for recommendations for public space designs that are adaptive to humid tropical climates, utilizing vegetation, reflective surface materials, and water elements as key strategies. Academically, this research contributes to the development of a thermal comfort-based urban design approach and the use of simulation technology to support urban environmental sustainability.

Based on the above background, this research aims to: (1) Determine the thermal comfort conditions of public open spaces in the Simpang Lima Pendopo area based on the results of ENVI-MET simulations. (2) Determine the comparison of changes in microclimate conditions between the 20%, 40%, and 60% optimization scenarios with respect to existing conditions, and the extent to which each scenario demonstrates the proportional impact of the applied design elements. (3) Determine which design scenario is most effective in improving the thermal comfort of public open spaces in the research area.

METHOD

The quantitative, prescriptive, and descriptive approaches used in this study were designed to analyze the thermal comfort of public open spaces at Simpang Lima Pendopo in a measurable and contextual manner. The quantitative approach was used to obtain an objective picture of thermal parameters such as air temperature, humidity, wind speed, and PMV values calculated through ENVI-MET simulations. While the descriptive approach empirically describes the existing conditions of outdoor spaces to understand the area's microclimate characteristics. The prescriptive approach was then used to formulate design solutions based on the simulation results, ensuring that the resulting recommendations are applicable and targeted. All three were combined through stepwise optimization scenarios of 20%, 40%, and 60%, referring to the surface energy balance of Oke (1987) and research by Bruse & Fleer (1998), Shashua-Bar & Hoffman (2000), and Ng et al. (2012), which demonstrated that this moderate range of changes is effective in assessing microclimate responses without significantly altering the area's morphology. This research is based on the thermal comfort theories of Givoni (1998) and ASHRAE (2017), which emphasize that comfort conditions are determined by air temperature, humidity, wind, and solar radiation; as well as the microclimate and Urban Heat Island theories of Oke (1987) and Santamouris (2014), which explain how hard surfaces and vegetation affect area temperature. Public open space design principles according to Carmona et al. (2010) and Gehl (2010) reinforce the importance of the physical quality of outdoor spaces, while research by Bruse & Fleer (1998), Shashua-Bar & Hoffman (2000), and Bowler et al. (2010) explains the effects of vegetation, surface materials, and water elements on reducing air temperature through shading, evapotranspiration, and evaporative cooling. The SNI 6390:2011 standard, ASHRAE (2017), and the ENVI-MET guidelines complement the theoretical basis as a reference for outdoor thermal comfort parameters. The research site at Simpang Lima Pendopo was divided into five zones to understand its socio-spatial characteristics—an education zone, an icon and street vendor center, a commercial and culinary corridor, a mixed-use business area, and small-scale activity spaces—as well as a pedestrian corridor, which is the most critical route due to its hard pavement and minimal vegetation. This zoning served as a morphological framework, but microclimate analysis was not limited by zones because thermal phenomena are continuous and interact across space, thus treating the entire simulation domain as a single physical system.

Data collection was conducted through field surveys, observations, visual documentation, and an inventory of vegetation and surface materials to construct a physical model of the area. Climate data from BMKG, NASA POWER, and WorldClim were used as atmospheric boundary parameters. Spatial data from Google Earth, Bappeda, and topographic maps complemented the 3D model of the area in ENVI-MET. Literature reviews from Givoni, ASHRAE, Oke, Santamouris, and various microclimate studies supported the development of the analytical framework and interpretation of the results.

The analysis of the physical elements of public open spaces focused on vegetation, surface materials, water elements, and wind direction as factors influencing air temperature, humidity, and PMV. Vegetation was analyzed using LAD and LAI parameters, materials using albedo, heat capacity, and thermal conductivity, and water elements using evaporative cooling mechanisms, which, according to Shashua-Bar & Hoffman (2000), are effective in reducing air temperature. Thermal comfort parameters were measured using air temperature, humidity, wind speed, and PMV based on the Fanger (1970) model, which served as the primary evaluation indicators.

Simulation scenarios were developed using four models—existing, 20%, 40%, and 60% intervention—that modified vegetation, surface materials, and water elements to assess the area's thermal response. Each model was tested using ENVI-MET and then compared temporally and spatially. Data analysis was performed by extracting simulation results in the form of temperature, humidity, wind, and PMV distributions, then interpreting them descriptively to formulate microclimate-based design recommendations.

The ENVI-MET model was validated through calibration of macroclimate data from BMKG, alignment of thermal patterns with empirical studies such as Ng et al. (2012) and Shashua-Bar & Hoffman (2000), and sensitivity analysis between scenarios to ensure logical change trends. Limitations of the study include the assumption of static atmospheric conditions, limited representation of anthropogenic heat sources, focus on specific physical elements, and reliance on secondary spatial and climate data. With this approach, the study produces a structured method that is able to read the thermal dynamics of the area in detail while providing a scientific basis for the design of public open spaces that are adaptive to humid tropical climates.

RESULTS AND DISCCUSION

Existing Conditions of the Simpang Lima Pendopo Area

This section summarizes the existing microclimate analysis of Simpang Lima Pendopo based on ENVI-met simulations at three key times—1:00 PM, 3:00 PM, and 5:00 PM—representing

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the initial heat peak, the heat transition, and the beginning of the afternoon cooling phase, respectively. The selection of these three intervals allows for more accurate readings of daily thermal dynamics because they reflect changes in solar radiation intensity, the heat storage capacity of materials, and the response of vegetation and open space to energy fluctuations.

Four key parameters—air temperature, relative humidity, wind speed, and Predicted Mean Vote (PMV) values—are used to understand the physical interactions that shape the area's thermal comfort. Air temperature analysis maps hotspots and areas still exhibiting natural cooling effects. Relative humidity is measured to determine how the local atmosphere changes with the rise and fall of heat and the contribution of vegetation evapotranspiration. Wind speed is evaluated to determine the area's ventilation patterns and the extent to which airflow can reduce heat accumulation. PMV values are used to interpret the physiological thermal comfort experienced by area users based on the combination of these parameters.

The readings at these three time points demonstrate the thermal transformation that occurs from midday to evening and also highlight how spatial configuration, material type, and vegetation distribution influence the microclimate response of each zone. With clear patterns of change, the most uncomfortable periods can be identified, as well as the areas most in need of physical intervention. This analysis serves as a foundation for determining the direction and priority of design strategies at the scenario stage, ensuring that each recommendation fully aligns with existing conditions, the temporal character of the area, and the contextual needs for thermal comfort improvements.

Microclimate Analysis: 1:00 PM, Beginning of Peak Heat

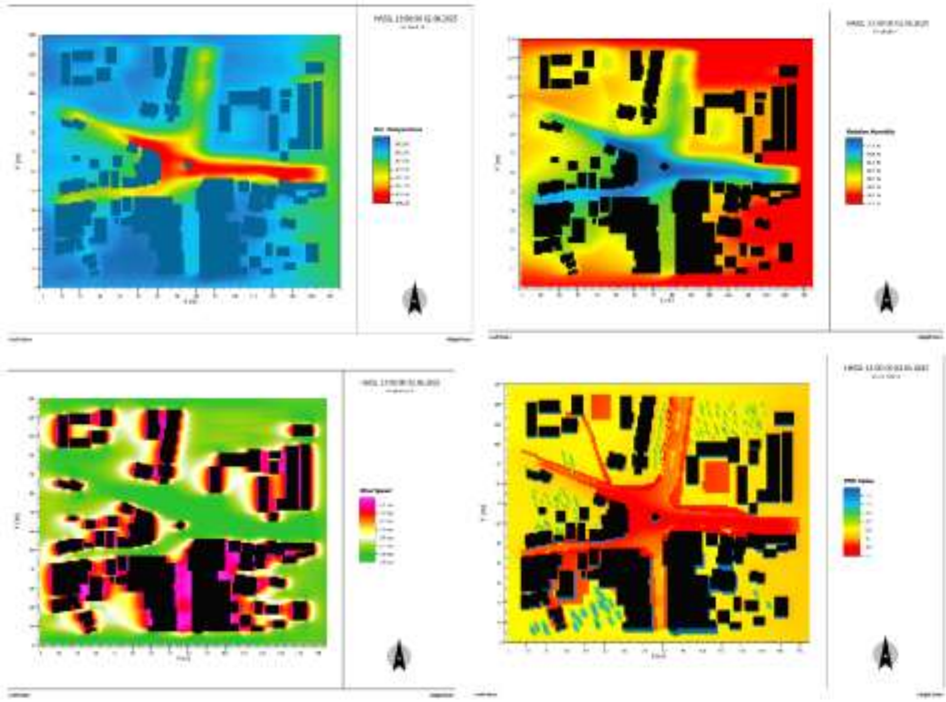

Figure 1. Visual Map of Existing Microclimate Conditions at 1:00 PM
Source: ENVI-met Simulation Results, 2025

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At 1:00 PM, Simpang Lima Pendopo was in the initial phase of peak heat when solar radiation reached its highest intensity and the area's hard surfaces began to release heat intensively. Air temperatures were recorded at 301.8–304.2 K (28.6–31.0°C), and the main corridor, dominated by asphalt and concrete, became the center of heat accumulation due to the high ability of these materials to absorb and store solar energy. The temperature map, dominated by yellow-orange to red colors, indicates that the central strip of the area functions as a heat corridor without the protection of vegetation or shading structures, resulting in direct radiation significantly increasing the surface radiation temperature. Areas protected by building mass did experience lower temperatures, but the coverage was very small and insufficient to mitigate the spread of heat within the area.

Relative humidity ranged from 77.3–92.3%, with an inverse pattern to temperature—the hottest areas exhibited lower humidity due to rapid drying, while shaded or windward areas retained higher humidity. Wind speeds were only 0.1–1.0 m/s, indicating minimal natural ventilation due to physical barriers such as buildings and large built-up surfaces. The lack of wind hindered convective heat loss and trapped heat longer in open spaces. This condition impacted PMV values, which reached 2.1–5.3, indicating that most areas were experiencing very hot conditions and causing high thermal stress for space occupants.

The combination of high temperature, unstable humidity, and weak ventilation indicates that the area lacks the adaptive capacity to mitigate heat during the most critical periods. These findings underscore the need for strategic interventions such as increasing shade vegetation, using highly reflective materials, and establishing natural ventilation pathways to reduce heat accumulation and improve thermal comfort during peak hours

Microclimate Analysis at 3:00 PM: Thermal Transition Phase

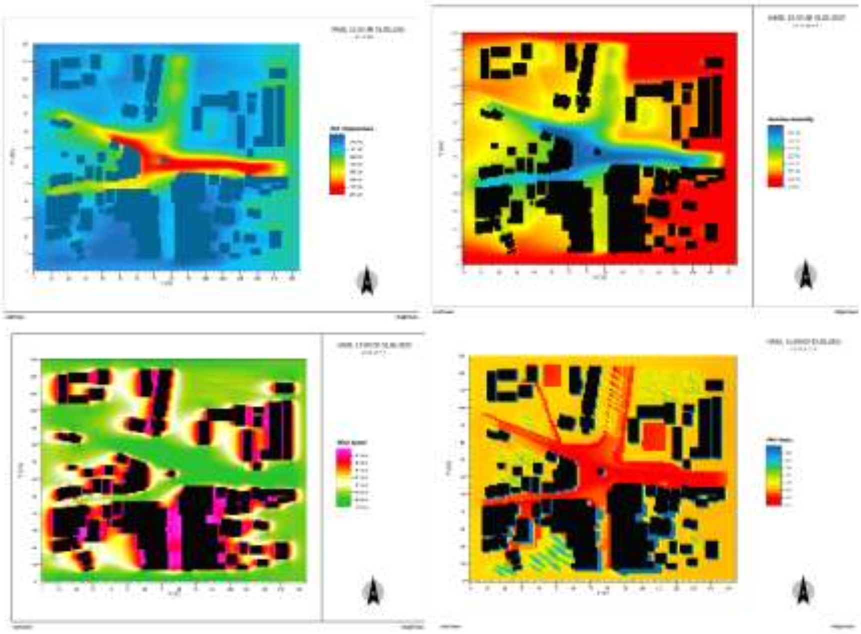

Figure 2. Visual Map of Existing Microclimate Conditions at 3:00 PM
Source: ENVI-met Simulation Results, 2025

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At 3:00 PM, Simpang Lima Pendopo entered a thermal transition phase when solar radiation began to weaken, but residual heat remained strongly stored on hard surfaces. Air temperatures remained high, at 301.8–304.2 K (28.6–31.0°C), with orange-red hues still dominating the main corridor. This condition indicates that asphalt and concrete, which have high thermal inertia, continue to slowly release heat, so the area remains hot despite reduced radiation intensity compared to 1:00 PM. The temperature decrease was only observed in the edge areas protected by building shade, but the distribution was too small to offset the dominant heat in the activity center.

Relative humidity increased slightly to 77.9–91.4%, but its distribution remained uneven. The central corridor, which was still hot, showed lower humidity due to rapid drying, while shaded areas retained higher humidity. Wind speeds in the range of 0.1–1.0 m/s indicate that natural ventilation remains weak, resulting in very slow heat loss through convective cooling. The impact is evident in PMV values, which remain between 2.0–5.4, indicating that the area's thermal conditions remain hot to very hot and have not yet reached a reasonable level of physiological comfort.

Overall, conditions at 3:00 PM indicate that the area is unable to effectively reduce heat during the afternoon transition phase due to a combination of hard surface thermal inertia, minimal shading vegetation, and poor ventilation. Without interventions such as increasing vegetation cover, modifying materials with higher albedo, or opening wind channels, thermal discomfort will persist until nightfall.

Microclimate Analysis 17.00 Hot Cooling Phase

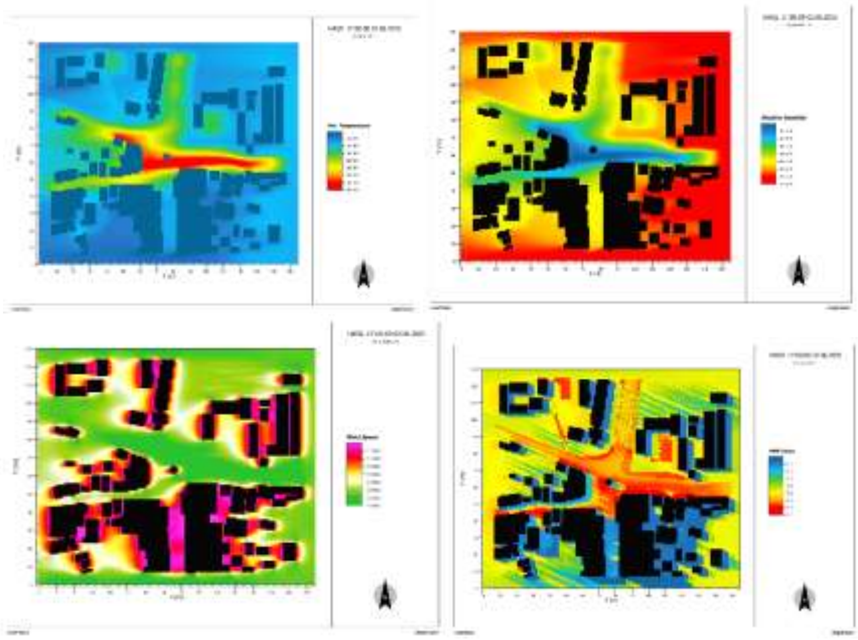


Figure 3. Visual Map of Existing Microclimate Conditions at 5:00 PM
Source: ENVI-met Simulation Results, 2025

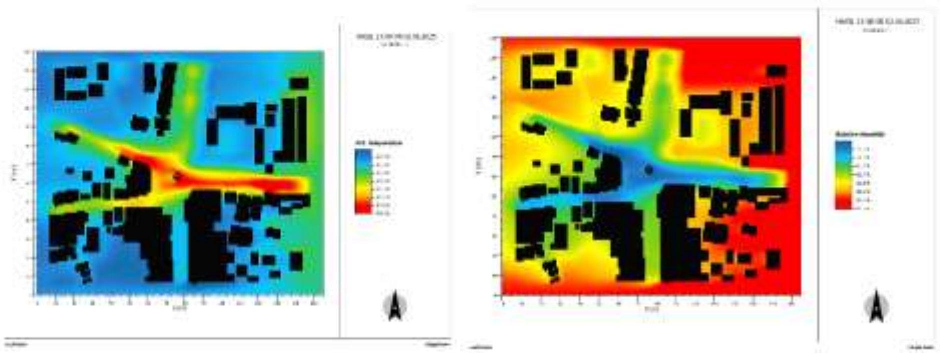
At 5:00 PM, Simpang Lima Pendopo entered a cooling phase when solar radiation weakened and surface heat loss began to dominate. Air temperatures dropped to 300.5–302.4 K (27.3–29.2°C), indicating a clear improvement compared to the peak heat period. The temperature map shows a predominance of blue-green hues in the edge areas that had received lower radiation since the beginning of the day, while faint yellow to red hues persisted in the main west–east corridor due to residual heat from asphalt and concrete. This indicates that despite the temperature decrease, the region's cooling response remained uneven due to hard materials' high heat storage capacity.

Relative humidity increased to 82.3–92.8% as the temperature decreased, with cooler areas exhibiting higher humidity. Zones that still retained residual heat continued to have slightly lower humidity values, although the difference was less pronounced. Wind speeds ranged from 0.1–1.1 m/s, with a more stable pattern due to weakened surface heating, but airflow remained restricted by building barriers. This resulted in a decrease in PMV values to 1.2–3.1, indicating a significant improvement in thermal comfort from “very hot” to “warm” to “slightly hot,” although not yet reaching optimal conditions due to residual surface heat and poor ventilation.

A 20% optimization scenario was then analyzed as an initial step for low-scale physical interventions, including the addition of linear vegetation, increased green cover on pedestrian paths, and the installation of small-scale water elements. The analysis was conducted at 1:00 PM, 3:00 PM, and 5:00 PM to observe thermal changes during three critical phases—peak heat, heat transition, and afternoon cooling. Four key parameters—air temperature, relative humidity, wind speed, and PMV—were used to evaluate the effectiveness of the interventions.

Temperature was monitored to assess local heat loss, while humidity was evaluated to gauge the contribution of additional vegetation evapotranspiration. Wind speed was used to determine whether linear vegetation affected airflow, and PMV served as a direct indicator of comfort for space users. Simulation results showed that a 20% intervention began to provide initial improvements in areas receiving additional vegetation and water elements, but the impact was still limited because the scale of the intervention was not large enough to significantly alter the area's thermal conditions. These findings provide an important basis for determining improvement steps toward the 40% and 60% optimization scenarios, allowing subsequent design strategies to be more precisely targeted to the area's thermal comfort needs.

20% Scenario 1:00 PM



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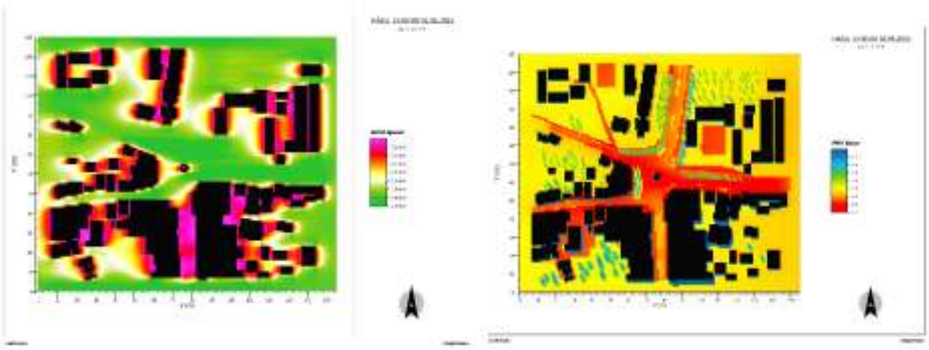

Figure 4. Visual Map of 20% Optimization Conditions for Microclimate at 1:00 PM
Source: ENVI-met Simulation Results, 2025

The simulation results for the 20% optimization scenario at 1:00 PM show that this low-scale intervention has not significantly changed the thermal characteristics of the area. Air temperatures remained in the high range of 301.7–304.1 K (28.5–31.0°C), with maximum values still reaching 304.1 K in the main corridor, which is dominated by asphalt and concrete. The addition of linear vegetation only resulted in local temperature reductions in the directly shaded areas, with minimum values around 301.7–302.0 K. However, the effect did not extend to the main activity zone because the unchanged surface material remained a residual heat source. Consequently, the temperature distribution pattern in this scenario remained very similar to existing conditions.

Relative humidity ranged from 77.2–92.3%, indicating a nearly identical hygrothermal pattern as before. Areas shaded by vegetation experienced increased humidity, but the thermal corridor continued to exhibit lower RH, thus maintaining a clear hygrothermal imbalance. Wind speeds also remained unchanged at 0.1–1.0 m/s, indicating that linear vegetation was unable to influence ventilation patterns due to the dominance of physical barriers from buildings and the continued trapping of airflow during peak heat hours.

PMV values in this scenario ranged from 2.1–5.3, indicating that extreme heat stress still dominated open spaces, particularly in the main corridor, which frequently reached values above 4.0, categorizing them as "very hot." A decrease in PMV was only observed in small shaded areas around additional vegetation, with values approaching 2.1–2.5, but this was very limited in extent and did not provide a significant improvement in overall comfort for the space's users.

Overall, the 20% optimization scenario produced only partial and localized improvements without significantly reducing the area's heat load. The dominance of high temperatures, unstable humidity, weak wind speeds, and persistently extreme PMV values indicate that low-scale interventions were insufficient to alter the area's thermal conditions. These findings emphasize the need to increase the intensity of interventions in the 40% and 60% scenarios to achieve broader, more consistent temperature reductions, targeting key activity zones that have historically been the focus of thermal discomfort.

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20% Scenario 3:00 PM

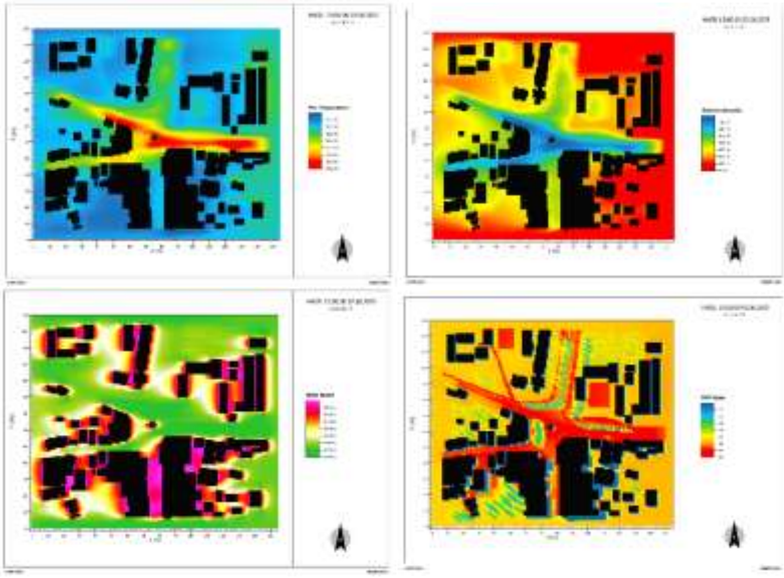

Figure 5. Visual Map of 20% Optimization Conditions for Microclimate at 3:00 PM
Source: ENVI-met Simulation Results, 2025

The simulation results for the +20% scenario at 3:00 PM show that the area is still in the residual heat release phase, so thermal conditions remain high even though solar radiation is starting to decrease. Air temperatures range from 301.7–304.1 K, indicating that hard surfaces—particularly asphalt and concrete in the main corridor—are still storing and slowly releasing heat. Because this scenario does not include material changes, temperature decreases only occur in areas directly shaded by additional linear vegetation, so temperature distribution remains uneven and the center of the corridor continues to act as a heat sink.

Relative humidity is between 78.2–91.4%, with a slight increase in areas covered by new vegetation, while exposed zones still experiencing surface heating show lower RH values. This demonstrates that mild interventions can only modify humidity locally without significantly altering the region's hygrothermal conditions.

Wind speeds remained low, at 0.1–1.0 m/s, indicating that the spatial configuration still hindered natural ventilation. Linear vegetation at the 20% intervention level was not large enough to influence airflow patterns or create new ventilation pathways, so the capacity for convective heat loss remained limited. As a result, residual heat continued to dominate the area's thermal conditions during the afternoon transition phase.

PMV values ranged from 2.0–5.3, indicating that hot to very hot conditions persisted throughout the open space. Although slightly lower than at 1:00 PM, PMV values at 3:00 PM remained well above the comfort threshold, indicating that thermal perceptions of public space users remained very uncomfortable.

Overall, the +20% scenario at 3:00 PM shows that light vegetation interventions were unable to reduce daily heat accumulation and did not produce significant thermal changes at the area scale. This underscores the need to increase the scope of interventions in the 40%

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and 60% scenarios to achieve more widespread and effective temperature reductions and comfort improvements.

20% Scenario at 5:00 PM

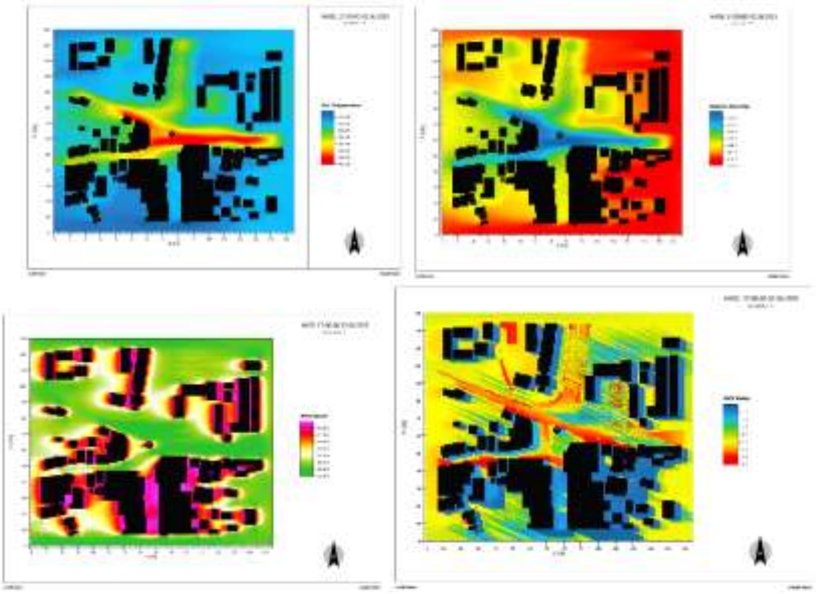

Figure 6. Visual Map of 20% Optimization Conditions for Microclimate at 5:00 PM
Source: ENVI-met Simulation Results, 2025

At 5:00 PM in the 20% optimization scenario, thermal conditions began to improve as solar radiation weakened. Air temperature dropped to 300.4–302.1 K (27.2–28.9°C). The temperature decrease was most pronounced in areas with added linear vegetation, with values approaching 300.4–300.7 K. However, the main corridor, covered with hard pavement, still retained residual heat of up to 302.0–302.1 K, indicating that the cooling was due more to the time of day (afternoon) than to the effectiveness of the 20% intervention.

Relative humidity increased to 83.3–92.9%. Vegetated areas showed a more consistent increase in humidity due to evapotranspiration, while the hot pavement zone maintained a lower relative humidity (83–85%), resulting in uneven hygrothermal patterns. Wind speeds ranged from 0.1–1.1 m/s, indicating ventilation stagnation and no significant changes in airflow; linear vegetation was not yet strong enough to alter wind paths or increase heat loss through advection.

PMV values decreased to 1.2–3.1, indicating improved comfort, particularly in areas that began to cool toward the afternoon. However, the main corridor remained in the moderately hot to hot range due to residual heat. This improvement reflects a temporal effect—namely, natural afternoon cooling—rather than the structural impact of the 20% intervention.

Overall, the 20% optimization scenario at 5:00 PM indicates that passive cooling is insufficient to address daily heat accumulation, particularly in high-heat-capacity materials. Discomfort in the main corridor persisted, necessitating more extensive interventions in the

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40% and 60% scenarios to ensure more even distribution of cooling and significantly improve comfort in the central activity zone.

Thermal Conditions in the 40% Optimization Scenario of the Simpang Lima Pendopo Area

The 40% optimization scenario is an intermediate intervention stage that introduces more substantial physical changes to the area than the 20% scenario. In this stage, linear vegetation is expanded into layered vegetation consisting of tall trees, shrubs, and groundcover along pedestrian paths, while shade trees are planted in the median, and pedestrian materials are replaced with high-albedo, more permeable surfaces. This intervention aims to reduce direct radiation by increasing vertical shading while simultaneously suppressing surface heat absorption through the material's high reflectance and heat dissipation capacity. Therefore, the 40% scenario not only increases green cover but also strategically alters the area's thermal structure through the integration of vegetation, surface materials, and spatial configuration.

Evaluations were conducted at 1:00 PM, 3:00 PM, and 5:00 PM using four microclimate parameters: air temperature, relative humidity, wind speed, and PMV, to comprehensively assess the intervention's effectiveness. Simulation results show a more consistent temperature reduction and improvement in thermal comfort in the layered vegetation areas and pedestrian paths with new materials, although cooling is less uniform in corridors blocked by building mass. Overall, this medium-scale intervention has a significant thermal impact, but a higher intensity, such as that in the 60% scenario, is still needed to address residual heat from the hard pavement and buildings and achieve uniform thermal comfort across the area.

40% Scenario 1:00 PM

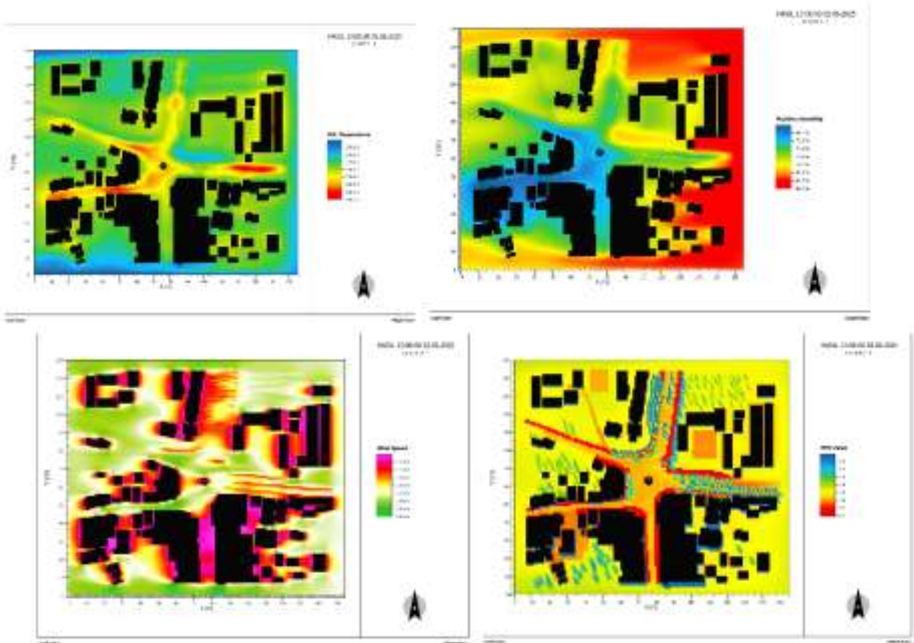


Figure 7. Visual Map of 40% Optimization Conditions for Microclimate at 1:00 PM
Source: ENVI-met Simulation Results, 2025

At 1:00 PM, the 60% optimization scenario, which integrates three-layer vegetation, new high-albedo and permeable pavement, and optimally functioning water elements, shows a significant temperature decrease despite still having maximum solar radiation. The air temperature is 298.7–300.3 K (25.55–27.15°C), with fully intervening pedestrian paths and vegetated medians reaching 298.7–299.2 K (25.55–26.05°C), visible as a blue-green gradient on the temperature map. The uninterrupted area remained hot, at 299.8–300.3 K (26.65–27.15°C), indicating that layered shading, strong evapotranspiration, and reflective materials significantly reduced heat accumulation during peak hours.

Relative humidity ranged from 67.7–80.7%, with the highest values in vegetated areas and near water bodies, as evapotranspiration increases hygrothermal stability. The existing pavement area showed a lower RH of 67–70%, but the spatial disparity was smaller than in the 40% scenario. Wind speeds of 0.1–1.0 m/s did not significantly change at the macro level, but layered vegetation and permeable surfaces created microturbulence that facilitated local heat loss, particularly in previously stagnant pedestrian paths.

PMV values ranged from 1.2–4.5, with the intervention area reaching a much more comfortable 1.2–2.0 (“warm”), while the uninterrupted zone remained close to 4.5, indicating continued discomfort. Overall, the 60% scenario successfully reduced the daily heat load, increased microhumidity, and substantially reduced PMV, resulting in significantly more comfortable thermal conditions than both the existing conditions and the 40% scenario.

40% Scenario 3:00 PM

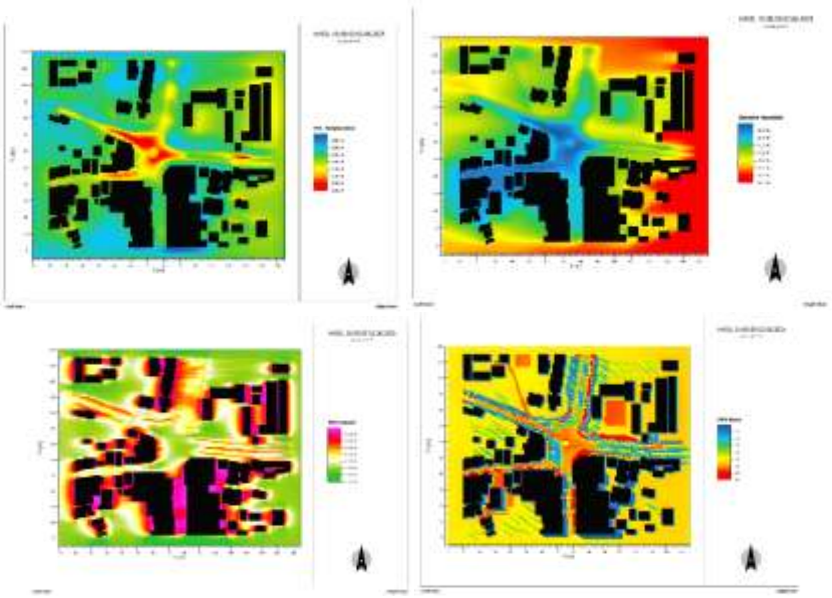


Figure 8. Visual Map of 40% Optimization Conditions for Microclimate at 3:00 PM
Source: ENVI-met Simulation Results, 2025

At 3:00 PM, the 60% optimization scenario with three-layer vegetation, high-albedo and permeable pavement, and stable water elements showed a significant thermal response even though the area entered the heat transition phase. Air temperatures were 298.7–300.2 K (25.55–27.05°C), with the fully intervening pedestrian path covered by tiered vegetation and reflective surfaces showing lower temperatures of 298.7–299.1 K (25.55–25.95°C). The

Jurnal Multidisiplin Sahombu
Volume 5, Number 08, 2025, DOI 10.58471/jms.v5i08
ESSN 2809-8587 (Online)
https://ejournal.seaninstitute.or.id/index.php/JMS/index

temperature map displays a blue-green gradient in this area, indicating reduced heat accumulation due to the combination of vertical shading and reduced radiation absorption. In contrast, the non-intervention area maintained a higher temperature of 299.8–300.2 K (26.65–27.05°C), visible as a predominance of yellow-orange hues on the old pavement, thus maintaining a strong thermal difference between the intervention and non-intervention zones.

Relative humidity ranged from 68.0–80.5%, with higher values in the three-layer vegetation area due to stable evapotranspiration, while the uninterrupted hard surface maintained a lower RH. Wind speeds of 0.1–1.0 m/s indicated no significant change in macro-ventilation, but micro-turbulence under the vegetation canopy helped reduce air stagnation and accelerated local heat loss on the pedestrian pathway. PMV values ranged from 1.3–4.3, with the intervention zone reaching 1.3–2.0 ("warm"), still comfortable for outdoor activities, while the non-intervention area maintained a high PMV approaching 4.3, indicating continued discomfort. Overall, the 60% scenario at 3:00 PM successfully maintained the region's thermal stability and significantly improved human comfort as the region entered the afternoon cooling phase.

40% Scenario at 5:00 PM

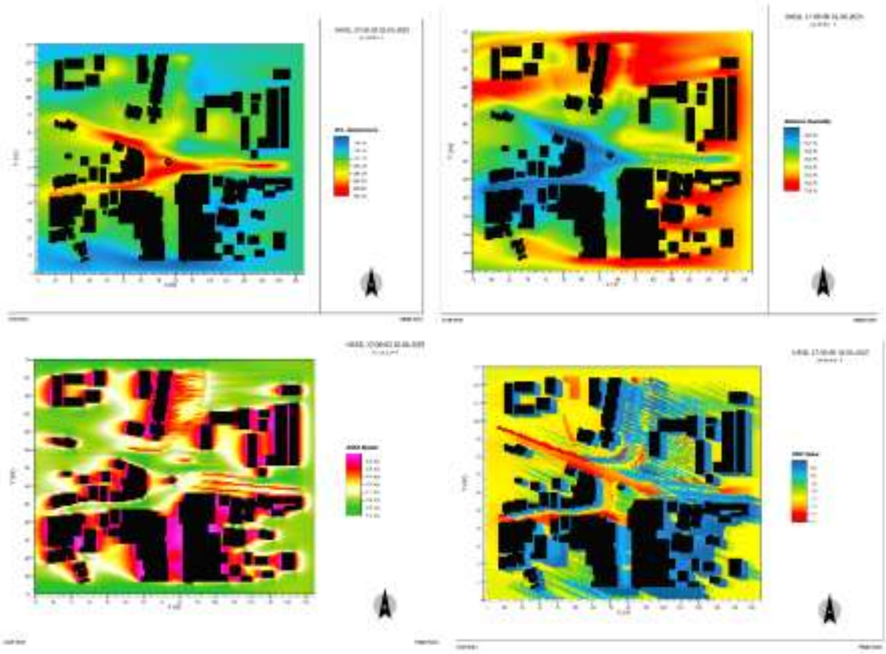


Figure 9. Visual Map of 40% Optimization Conditions for Microclimate at 5:00 PM
Source: ENVI-met Simulation Results, 2025

At 5:00 PM, the 40% optimization scenario demonstrated the most effective cooling phase, with air temperatures of 298.1–300.1 K (25.0–27.0°C). The intervention area, planted with layered vegetation along the pedestrian path and median, reached the lowest temperature of 298.1–298.6 K (25.0–25.5°C), while the unmodified hard pavement remained hot at 300.0–300.1 K (26.9–27.0°C). The temperature map shows that layered shading and reflective materials accelerate local heat loss, resulting in faster cooling of the intervention area compared to existing conditions and the 20% scenario.

Relative humidity was 68.9–79.5%, with the highest values in the vegetated area due to evapotranspiration from the multi-story structure. Wind speeds of 0.1–1.1 m/s remain low at the macro level, but microturbulence beneath the vegetation canopy facilitates surface heat dissipation. PMV values range from 0.6–3.0, with the intervention area reaching 0.6–1.2, approaching the comfortable-warm category. Overall, the 40% scenario in the afternoon successfully improves thermal comfort, reduces heat load, stabilizes local humidity, and creates a more balanced microclimate compared to the existing condition.

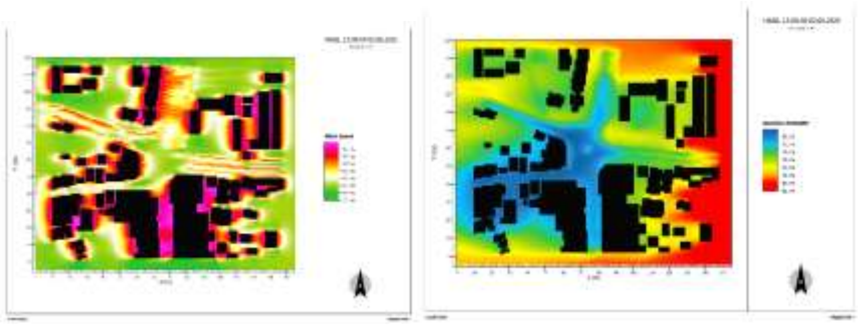
Regional Thermal Conditions in the 60% Optimization Scenario

The +60% optimization scenario is the highest level of intervention in the Simpang Lima Pendopo area, involving comprehensive open space redevelopment. Interventions include the implementation of three layers of vegetation in the core area and along pedestrian paths, replacement of pavement with reflective and permeable materials, and the addition of a reflective pool at the roundabout for both aesthetic and thermal control purposes. These three elements work in an integrated manner to lower air temperature, stabilize humidity, increase microventilation, and reduce thermal discomfort throughout the area.

The analysis was conducted at 1:00 PM, 3:00 PM, and 5:00 PM to represent the peak heat phase, heat transition, and afternoon cooling. At 1:00 PM, interventions aimed to reduce radiation exposure and heat storage in the pavement; at 3:00 PM, the intervention focused on residual heat release through the role of vegetation, permeable materials, and water elements; while at 5:00 PM, the +60% scenario assessed the ability of the +60% scenario to reduce temperatures and stabilize the microclimate toward thermal comfort.

Compared to the +20% scenario, which only had local effects, and the +40% scenario, which began to show spatial improvements, the +60% scenario resulted in more uniform changes in thermal patterns. Three layers of vegetation reduced direct radiation and increased evapotranspiration, permeable reflective materials suppressed heat storage, while reflective pools created cooler microclimate zones. The ENVI-met simulation results are presented through maps of the distribution of air temperature, relative humidity, wind speed, and PMV, as well as tables of minimum and maximum values. The analysis compares the main intervention areas—pedestrian corridors, core open spaces, and roundabouts—with existing conditions and the 20% and 40% scenarios, demonstrating the extent to which the +60% scenario is able to create more consistent thermal comfort across public spaces.

60% Scenario 1:00 PM



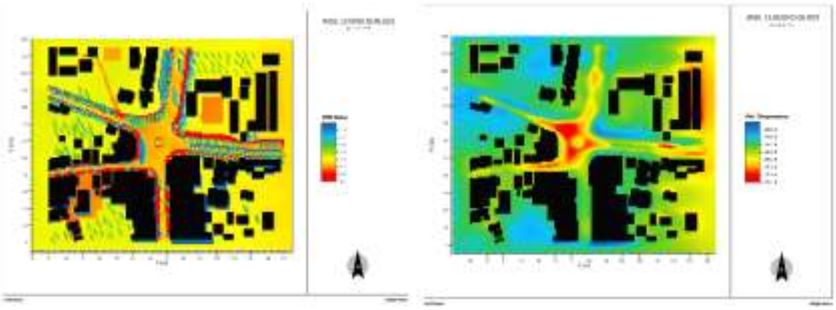
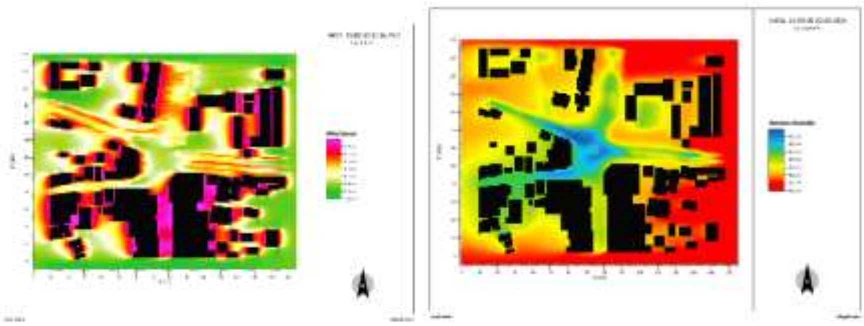


Figure 10. Visual Map of 60% Optimization Conditions for Microclimate at 1:00 PM
Source: ENVI-met Simulation Results, 2025

At 1:00 PM, the 60% optimization scenario showed the most significant temperature reduction compared to the previous scenario, with air temperatures of 298.7–300.3 K (25.55–27.05°C). The full intervention area, which features three layers of vegetation, reflective/permeable materials, and water elements such as fountains and reflecting pools, had a lower temperature of 298.7–299.2 K (25.55–26.0°C), appearing as a blue-green gradient on the temperature map. The unmodified hard pavement remained hot at 299.8–300.3 K (26.5–27.05°C). The evaporative effect of the water elements amplifies local cooling, reducing heat accumulation in hot spots.

Relative humidity ranged from 68.8–82.3%, highest in vegetated areas and near water elements, reflecting increased evapotranspiration that stabilized the microclimate. Wind speeds of 0.1–1.0 m/s did not significantly change at the macro level, but layered vegetation and permeable surfaces increased micro-air movement, reducing heat stagnation in circulation paths. PMV values decreased to 1.1–4.2, with the intervention area reaching 1.1–1.8 (warm-comfortable category). These results confirm that the combination of three layers of vegetation, reflective/permeable materials, and water elements is the most effective intervention for reducing temperatures by ±2–4°C and improving thermal comfort in the area during peak radiation hours.

60% Scenario 3:00 PM



Jurnal Multidisiplin Sahombu
Volume 5, Number 08, 2025, DOI 10.58471/jms.v5i08
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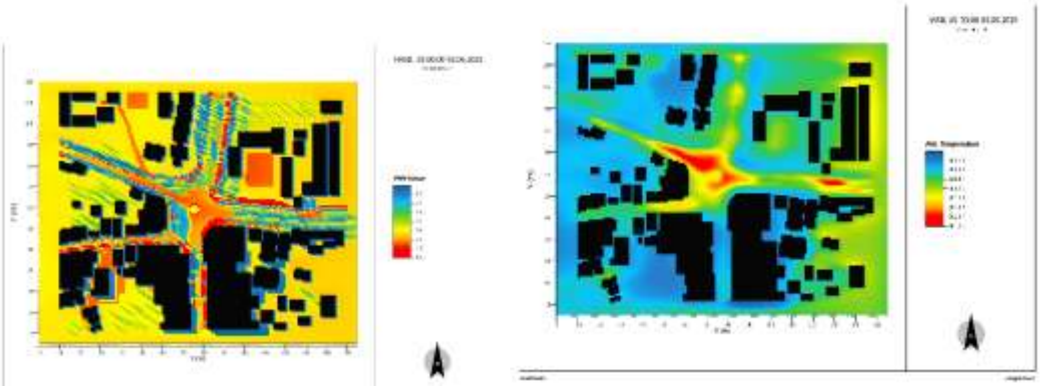
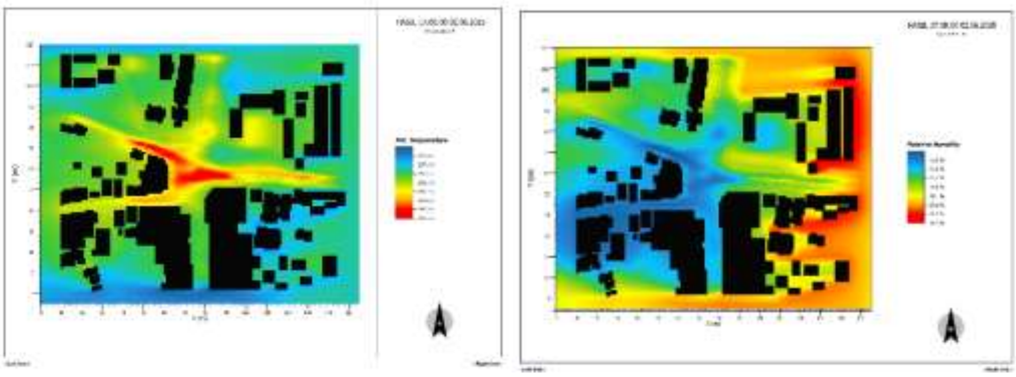


Gambar 11. Peta Visual Kondisi Optimasi 60% Mikroklimat Jam 15.00
Source: ENVI-met Simulation Results, 2025

At 3:00 PM, the 60% optimization scenario demonstrated continued strong thermal performance during the heat transition phase. Air temperatures were at 298.7–300.2 K (25.55–27.05°C), with the full intervention area—the shaded pedestrian path, median, and zone covered with three layers of vegetation, as well as reflective/permeable surfaces and water elements—showing a lower temperature of 298.7–299.1 K (25.55–25.95°C), visible as a blue-green gradient on the temperature map. The non-intervention area with existing materials remained hot at 299.8–300.2 K (26.65–27.05°C), marked by a dominant yellow-orange hue, indicating that the 60% intervention combination was still effective in containing heat accumulation even though radiation began to decrease.

Relative humidity ranged from 68.0–80.5%, highest in the layered vegetation zone and near water elements due to active evapotranspiration and evaporative cooling. Wind speeds remained at 0.1–1.0 m/s, but microturbulence under the vegetation canopy helped reduce air stagnation on pedestrian paths. PMV values ranged from 1.3–4.3, with the intervention area reaching 1.3–2.0 (an acceptably warm category), while the non-intervention zone still showed high PMVs approaching 4.3, indicating significant discomfort. Overall, the 60% scenario at 3:00 PM maintained thermal stability and improved public space user comfort during the transition period to the afternoon.

60% Scenario at 5:00 PM



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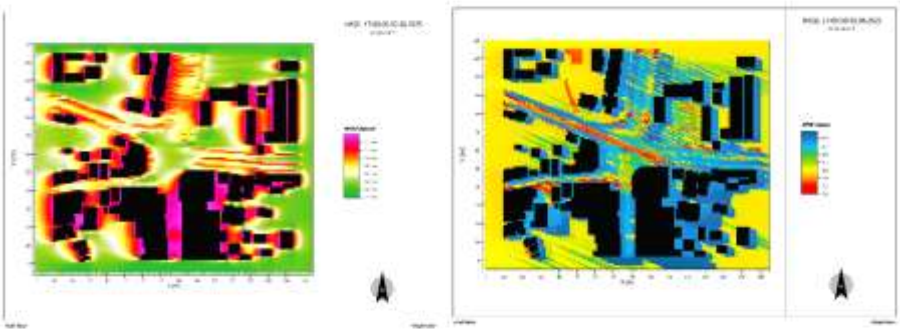

Figure 12. Visual Map of 60% Optimization Conditions of Microclimate at 17.00
Source: ENVI-met Simulation Results, 2025

At 5:00 PM, the 60% optimization scenario showed a significant increase in thermal comfort compared to the daytime. Air temperatures were 297.4–298.9 K (24.25–25.75°C), with the full intervention area—a tiered vegetated pedestrian path, a canopied median, and a green space with a reflective surface—showing the lowest temperature of 297.4–297.9 K (24.25–24.75°C), shown as a blue-green gradient on the map. The existing pavement still retained residual heat of 298.5–298.9 K (25.25–25.75°C), but the overall thermal distribution was more even and hotspots were reduced.

Relative humidity increased to 72.1–83.1%, highest in the vegetation zone and near the water element due to evapotranspiration and evaporative cooling. Wind speeds ranged from 0.1–1.0 m/s, with local airflow increasing in vegetation corridors, resulting in more effective heat dissipation. PMV values ranged from 0.4–2.6, with the intervention zone reaching 0.4–1.0 ("mild warmth"), while the non-intervention area remained at 1.6–2.6. The 60% scenario in the afternoon confirmed that the integration of tiered vegetation, reflective/permeable surfaces, and reflective water elements worked synergistically to lower temperatures, even out thermal distribution, and create more stable thermal comfort for public space users.

Comparison Between Optimization Scenarios

This section presents a comprehensive comparison between existing conditions and three optimization scenarios (20%, 40%, and 60%) at three observation times: 1:00 PM, 3:00 PM, and 5:00 PM. The comparison was conducted using four key microclimate parameters: air temperature, relative humidity, wind speed, and Predicted Mean Vote (PMV) to assess the extent to which each level of physical intervention contributed to improved thermal comfort. This approach allows for the identification of progressive patterns between scenarios, as well as areas most responsive to design changes. The findings from this analysis provide a strong basis for recommending more effective public open space planning strategies in subsequent design phases.

Comparison of Air Temperature Changes

Table 1. Average Air Temperature Values Between Scenarios

Time	Existing	Optimization 20%	Optimization 40%	Optimization 60%
13.00	302.8 K (29.65°C)	302.6 K (29.45°C)	300.9 K (27.75°C)	299.4 K (26.25°C)
15.00	302.7 K (29.55°C)	302.5 K (29.35°C)	300.8 K (27.65°C)	299.9 K (26.75°C)
17.00	301.4 K (28.25°C)	301.1 K (27.95°C)	299.8 K (26.65°C)	298.2 K (25.05°C)

The decrease in air temperature shows a progressive trend from the existing conditions to the 60% optimization scenario. At 1:00 PM, the existing conditions recorded an average temperature of 302.8 K (29.65°C), while the 20% scenario only reduced it by ±0.2°C, indicating that limited interventions were not sufficient to break the heat accumulation in the hard pavement. The 40% scenario began to provide significant improvements with an average of 300.9 K (27.75°C), particularly on the vegetated pedestrian path. The most significant decrease occurred in the 60% scenario, with an average temperature of 299.4 K (26.25°C), a decrease of approximately 3°C from the existing. This pattern remained visible at 3:00 PM and 5:00 PM, where the 60% scenario consistently recorded the lowest temperatures and the most even temperature distribution. Comparisons between scenarios show that the combination of three-layer vegetation, reflective-permeable materials, and water elements in the 60% scenario creates the most significant temperature reduction, both in absolute and spatial terms. Cooling by 3–4°C not only suppresses hotspots but also produces a more homogeneous temperature gradient across public spaces, making the 60% scenario the most effective design intervention for reducing the area's heat load.

Relative Humidity Comparison

Table 2. Average Humidity Values Between Scenarios

Time	Existing	Optimization 20%	Optimization 40%	Optimization 60%
13.00	84%	84%	80%	76%
15.00	84%	85%	81%	78%
17.00	88%	89%	84%	80%

Relative humidity shows a gradual decrease as air temperature decreases. Under existing conditions, high RH (84–92%) is driven by high surface temperatures and poor ventilation. The 20% scenario does not produce significant changes, while the 40% scenario begins to show humidity stabilization through layered vegetation evapotranspiration. The 60% scenario produces the most balanced conditions with RH of 76–80%, indicating that air cooling through vegetation shading and water evaporation stabilizes the micro-atmosphere without excessively increasing humidity.

The humidity balance in the 60% scenario is an important finding, as excessively high RH can increase the sensation of heat. With a significant decrease in temperature and a more stable RH, thermal comfort improves substantially compared to the other scenarios.

Wind Speed Comparison

Table 3. Average Wind Speed Values Between Scenarios

Time	Existing	Optimization 20%	Optimization 40%	Optimization 60%
13.00	0.6 m/s	0.6 m/s	0.7 m/s	0.8 m/s
15.00	0.5 m/s	0.6 m/s	0.7 m/s	0.8 m/s
17.00	0.6 m/s	0.7 m/s	0.8 m/s	0.9 m/s

Wind speed remained relatively unchanged due to the influence of building morphology. However, the 40% and 60% scenarios showed improvements in airflow quality. Layered vegetation at the 40% scenario began to break up stagnation, while the 60%

Jurnal Multidisiplin Sahombu
Volume 5, Number 08, 2025, DOI 10.58471/jms.v5i08
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scenario exhibited a more dynamic microflow pattern with an average value of 0.8–0.9 m/s, which helped accelerate surface heat dissipation.

The combination of layered vegetation and permeable pavement in the 60% scenario created much more effective microventilation than the previous two scenarios. This directly contributed to accelerated cooling and a reduction in PMV.

Comparison of PMV (Thermal Comfort)

Table 4. Average PMV Values Between Scenarios

Time	Existing	Optimization 20%	Optimization 40%	Optimization 60%
13.00	4.7	4.5	3.2	2.2
15.00	4.6	4.3	3.0	2.1
17.00	2.4	2.2	1.6	1.0

PMV showed the clearest improvement between scenarios. The existing and 20% scenarios were in the very hot category, while the 40% scenario was beginning to enter the moderate comfort level. However, the 60% scenario performed best, with an average PMV of:

a. 2.2 at 1:00 PM
b. 2.1 at 3:00 PM
c. at 5:00 PM

These values already fall into the warm-comfortable category, and only the 60% scenario successfully moved the area closer to the tropical public space thermal comfort standard. PMV of 0.4–2.6 in the intervention area demonstrates that the 60% scenario not only lowers temperatures but also provides stable, even, and most conducive thermal conditions for outdoor activities.

CONCLUSION

This study assessed the microclimate conditions of the Simpang Lima Pendopo area and the effectiveness of three levels of design interventions—20%, 40%, and 60%—in improving the thermal comfort of public open spaces. Based on ENVI-met simulations at 1:00 PM, 3:00 PM, and 5:00 PM, the existing area exhibited high heat stress due to the dominance of hard pavement, minimal shade vegetation, and limited micro-ventilation. All three optimization scenarios demonstrated improvements in thermal performance at varying intensities, with the 60% scenario proving to be the most effective, consistent, and providing the most significant thermal improvements across all microclimate parameters. The integration of three layers of vegetation, high-albedo and permeable surface materials, and water elements (reflective pools) significantly reduced air temperature, stabilized humidity, improved air circulation, and substantially reduced PMV. These findings confirm that landscape engineering based on tiered vegetation and thermal surface management is the most effective strategy for reducing heat loss in humid tropical urban areas. Air temperatures under existing conditions were high, particularly between 1:00 PM and 3:00 PM, averaging 29.5–31°C. The 20% intervention scenario only reduced temperatures by ±0.2°C, while the 40% scenario reduced temperatures by 1.2–1.8°C in the intervention area, particularly along the multi-vegetated pedestrian path. The 60% scenario showed the most significant reductions, at 3–4°C across all observation times, with afternoon minimum temperatures reaching 25°C, particularly in areas with multi-tiered vegetation and permeable-reflective surfaces. Existing relative humidity was 84–92%, with strong fluctuations due to surface heat. The 20% intervention did not significantly alter this pattern, while the 40% scenario stabilized humidity through vegetation evapotranspiration. The 60% scenario resulted in a more balanced humidity of 76–80%, indicating better thermal balance.

Wind speeds in the area remained low (0.1–1.1 m/s) due to the building's morphology. The 20% intervention had no significant impact, the 40% scenario began to improve micro-breeze in pedestrian paths, and the 60% scenario most effectively increased micro-ventilation by creating stable wind corridors and reducing air stagnation. The existing PMV values were in the "hot-very hot" category (2.1–5.4). The 20% intervention only reduced PMV locally, the 40% scenario improved comfort in vegetated areas, while the 60% scenario reduced PMV by 0.4–2.6, in the "warm-comfortable" category, particularly at 5:00 PM, demonstrating the effectiveness of the combination of three layers of vegetation, reflective materials, and water elements.

The 20% optimization had a local impact with minimal reductions in temperature and PMV, making it ineffective for the entire area. The 40% optimization showed a more even distribution of heat loss, with layered vegetation and reflective-permeable materials reducing hotspots, but not fully addressing residual heat. The 60% optimization resulted in the strongest thermal improvements across all parameters, lowering temperatures by 3–4°C, stabilizing RH, increasing wind flow, and significantly reducing PMV. This intervention eliminated hotspots, created uniform thermal comfort, and demonstrated consistency from peak heat to afternoon, making it the most effective scenario and highly suitable for use as a basis for area design.

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