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Simulation-based assessment of urban heat island mitigation in commercial districts

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Abstract. Commercial districts in tropical cities are especially vulnerable to the Urban Heat Island (UHI) effect, leading to higher outdoor air temperatures and poorer microclimate conditions. This study examines the efficiency of UHI mitigation strategies to lower the outdoor air temperature in a commercial area in Malang, Indonesia. The research utilized ENVI-met microclimate simulation software to analyse the effectiveness of different UHI mitigation strategies. Four mitigation strategies were developed: structural-based, vegetation-based, material-based, and an integrated mitigation approach. The results were compared to the current conditions. Simulations were conducted to represent the hottest day during the dry season, measuring air temperature at a height of 1.4 m throughout the day. The results indicate that all mitigation scenarios maintain a similar daily temperature pattern to the current condition, with peak air temperatures occurring in the early afternoon. The major difference among all mitigation strategies is the amount of cooling effect. The structural-based mitigation scenario provides the minimum amount of cooling effect, at 0.12 °C. The vegetation-based mitigation scenario provides 0.38 °C, while the material-based mitigation scenario provides 0.61 °C. The integrated mitigation scenarioproduced the greatest cooling effect, reducing the temperature by 0.86 °C. These findings demonstrate that integrated, multi-mechanism strategies can effectively reduce daytime heat exposure in tropical commercial areas, while also showing the need for additional comfort assessments that look beyond just air temperature.

Keywords: Air Temperature; Commercial District in Tropical City; ENVI-met; Microclimate Mitigation; Urban Heat Island

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1. Introduction

Urban Heat Islands (UHI) are becoming more prominent in the global environmental scale, especially in tropical cities. The increase in urban air temperature is attributed to more built structures, increased impervious surfaces, and the replacement of the natural land with unnatural materials [1,2]. In this context, commercial districts emerge as one of the most thermally stressful urban environments as studies show that commercial districts tend to have higher daytime thermal intensities compared to their surrounding urban areas [3–5]. In addition to increased temperature, the UHI have negative influences on public health as well as the outdoor environment [6]. This is especially pertinent to the commercial areas that are crucial for the everyday functions of a city. These conditions highlight the urgent need to develop and evaluate UHI mitigation strategies that can help improve thermal conditions in commercial districts.

Various strategies for reducing UHI in dense urban areas have been suggested, including vegetation improvement, changing materials, and modifying urban design [7]. Studies show that modifying vegetation and surface materials can help reduce heat buildup, while urban form features affect thermal conditions by controlling sunlight exposure and airflow [8–10]. To understand the complex interactions among urban shape, surface properties, vegetation, and microclimates, researchers often use simulation methods, with ENVI-met a common tool for evaluating the microclimatic effects of mitigation measures [11]. Despite the novelty and complexity of the proposed strategies, both empirical and simulation studies have shown that the results of these strategies are highly dependent on the specific characteristics of the urban form and climate, and thus cannot be generalized to all situations [12]. Although outdoor air temperature is a primary indicator in UHI research, many studies focus on typical climatic conditions. A review indicates most UHI research occurs in subtropical climates and regular seasons, with less attention given to extreme thermal periods in tropical environments [11]. As a result, there is limited information on the effectiveness of UHI mitigation strategies during peak heat periods in densely built tropical commercial districts.

This study seeks to evaluate the effectiveness of UHI mitigation strategies through ENVI-met microclimate simulations in a tropical commercial district, with particular emphasis on the outdoor air temperature at pedestrian height under peak dry season conditions. Interventions involving vegetation, materials, and structural are evaluated in relation to the prevailing urban conditions. The research seeks to quantify the effectiveness of these strategies in reducing the outdoor air temperature in dense tropical commercial districts, thereby providing useful insights to address the issue.

2. Methods

2.1. Study area

The study area is situated in the Pasar Besar commercial district of Malang City, Indonesia, serving as a main hub for trade and services (Fig. 1). This area features densely packed buildings, high land use intensity, predominantly impervious surfaces, and active commercial

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and traffic activities, represents a compact tropical commercial environment prone to elevated outdoor air temperatures. Pasar Besar was selected for its strategic commercial function and documented role as a localized UHI within Malang City. Previous micro-scale studies, including high-resolution UAV thermal imaging, show significant surface-driven heat build-up, with asphalt roads reaching daytime temperatures of up to 48.62 °C. Meanwhile, vegetated areas stay considerably cooler [13]. These characteristics indicate a strong micro-UHI effect, confirming that the area is suitable for assessing air temperature–based mitigation strategies in tropical commercial districts.

Figure 1. Location and placement of the study area.

2.2. ENVI-met microclimate modelling

ENVI-met is a 3D microclimate model that simulates interactions among the atmosphere, buildings, vegetation, and urban surfaces at a small scale. It uses Computational Fluid Dynamics (CFD) and the Reynolds-averaged Navier–Stokes (RANS) equations to model airflow, turbulence, heat transfer, and moisture exchange in urban environments [14]. ENVI-met functions at a suitable spatial resolution and includes surface energy balance calculations for soil, pavements, walls, and roofs, along with vegetation processes like shading and evapotranspiration [15]. This integrated framework allows the model to evaluate how urban design, material characteristics, and vegetation influence microclimatic conditions at pedestrian level, especially affecting air temperature. Owing to these features, ENVI-met has been widely applied in UHI studies to evaluate mitigation strategies, with validation studies generally reporting acceptable agreement between simulated and measured air temperature, despite known limitations in representing wind speed and radiative processes [11,16,17].

ENVI-met version 5.8.0 was used to simulate outdoor air temperature under current and mitigation scenarios in the study area. The model layout shows the physical design of the Pasar Besar commercial district, detailing building styles, street designs, surface materials, and existing greenery, all based on field observations and high-resolution satellite images. A

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horizontal grid resolution of 2×2×2 m was used to capture pedestrian-scale differences, along with a telescoping vertical grid to maintain accuracy near the ground and improve computational efficiency [15]. Meteorological boundary conditions were set using a simple forcing configuration and applied evenly across all scenarios. The simulation covers a full day cycle on the hottest day of the 2024 dry season, with meteorological inputs checked against the nearest official weather station. Wind speed was set at 0.1 m/s to simulate weak wind conditions and limit external atmospheric influence, ensuring that temperature changes mostly reflect local physical changes. All simulations lasted 12 hours, with the first 3 hours discarded for model spin-up [15,18]. The same numerical settings were applied to all scenarios to allow for easy comparison of outdoor air temperature responses. A summary of the ENVImet simulation setup and input parameters is shown in Table 1.

Table 1. Configuration and input parameters of ENVI-met simulations.

Parameter	Value
Parameters of the 3D Model Domain	
Domain size (XY)	400 m × 250 m
Number of horizontal grids (XYZ)	200 × 125 × 22
Grid resolution (dx, dy, dz)	2 m × 2 m × 2 m
Maximum building height	26 m
Total domain height	61 m
Vertical grid scheme	Telescoping grid
Telescoping start height	30 m
Vertical growth factor (dz)	20%
Distance from buildings to model edge	58 m
Nesting zone	5 grid cells on each side (total 40 m)
Distance from buildings to domain boundary	9 grid cells (18 m)
Input Parameters Used to Initialize the ENVI-met Simulation	
Start time	5:00 local time
Total Simulation	12 h
Boundary condition	simple Forcing
Wind speed at 10 m above ground	0.1 m/s
Wind direction	60°
Roughness length	0.01
Atmospheric temperature	min = 24 °C, max = 33 °C
Relative humidity at 2 m above ground	min = 36%, max = 84%

2.3. Mitigation scenarios and research framework

UHI mitigation strategies can be grouped based on their main physical mechanisms. These include changes to urban form, vegetation coverage, and surface material properties [8–10]. Previous studies show that altering pavement characteristics can change how heat is stored and exchanged. Additionally, urban layout affects solar exposure and air movement at the street level. Vegetation helps lower air temperatures through shading and evapotranspiration. This has been observed at both local and neighbourhood levels in tropical urban areas. These

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findings suggest that physical, space-based interventions are essential for managing outdoor air temperature in crowded urban settings. This study specifically looks at physical mitigation strategies that can be directly influenced by spatial and design choices. Five simulation scenarios were created: (1) the current baseline condition, (2) a structural intervention scenario, (3) a vegetation intervention scenario, (4) a material intervention scenario, and (5) an integrated scenario that combines all physical interventions to assess cumulative effects. The spatial arrangement of each scenario is summarized in Table 2 and shown in Figure 2.

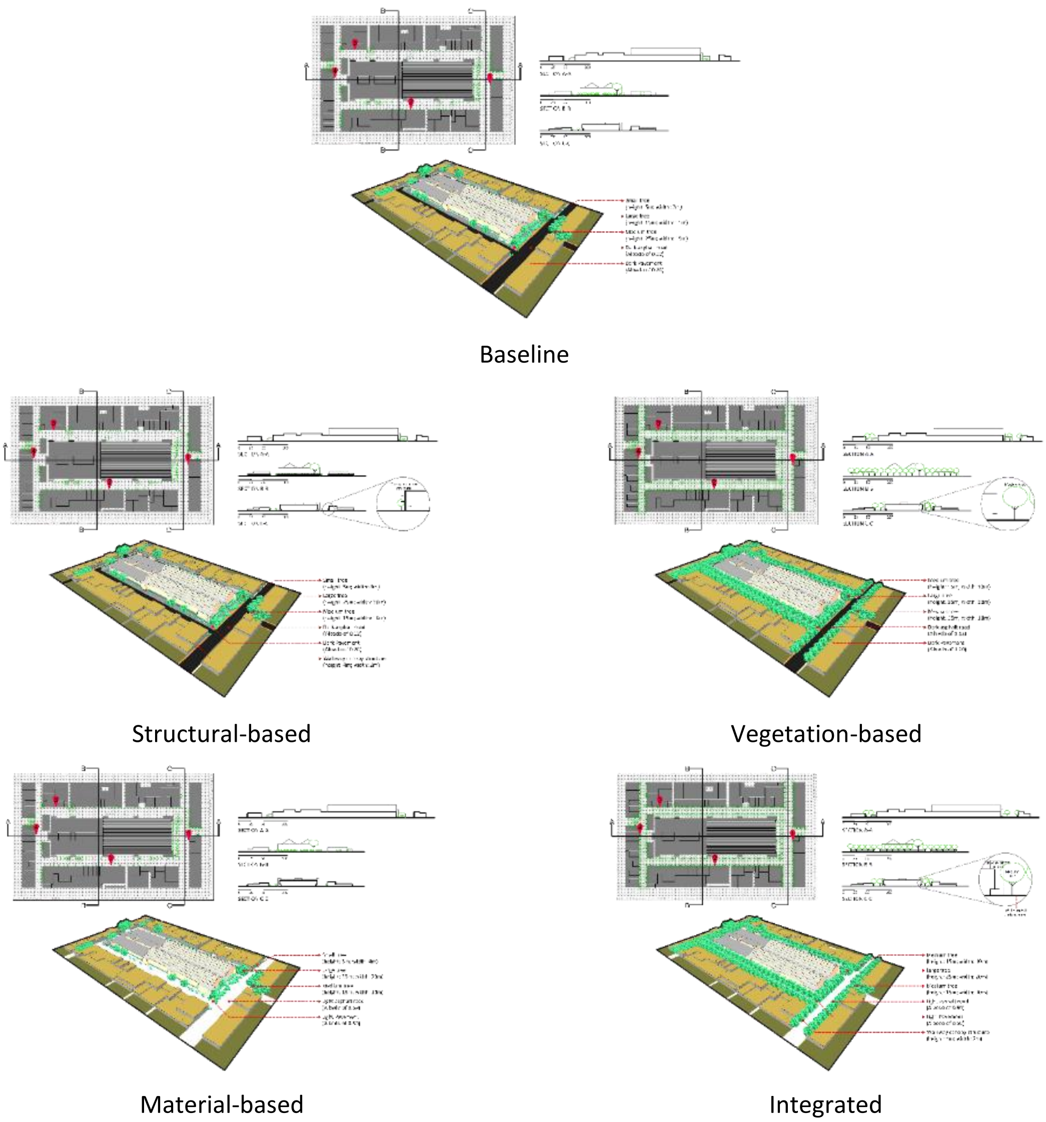

Figure 2. Spatial configuration of the baseline condition and UHI mitigation scenarios.

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Table 2. Description of UHI mitigation scenarios.

Parameter	Value
Baseline	Represents the current urban setup without any changes to building shapes, plant cover, or surface materials. This serves as the baseline for all comparison studies.
Structural-based intervention	Uses continuous concrete shading canopies that are about 2 m wide, installed 4 m above ground along pedestrian walkways and next to building facades. The goal is to reduce the sky view factor and direct sun exposure at the pedestrian level.
Vegetation-based intervention	Improves the current plant structure by adding medium-sized street trees, around 15 m tall, at regular intervals of about 10 m along pedestrian pathways. This also keeps the existing medium and large trees to improve shading and evapotranspiration.
Material-based intervention	Changes the thermal properties of hard surfaces by swapping low-reflective asphalt (0.12) and dark pavement (0.2) for higher-reflective asphalt (0.59) and concrete surfaces (0.5). This helps lower solar heat absorption and surface heat storage.
Integrated intervention	Brings together structural shading elements, enhanced street trees, and high-reflective materials in one scenario to assess the combined effects of decreased radiative exposure, increased evapotranspiration, and reduced surface heat buildup.

All mitigation scenarios were simulated with the same domain configurations, meteorological boundary conditions, and numerical settings to ensure they could be compared. Outdoor air temperature (Ta) at a height of 1.4 m above ground, which reflects conditions at pedestrian level, was used as the main performance indicator. We measured mitigation effectiveness using ΔTa, which is the difference in air temperature between each mitigation scenario and the existing baseline condition. The analysis took place at two spatial levels: (1) the area-averaged air temperature across the entire study domain to capture overall thermal changes, and (2) four selected receptor points that represent key pedestrian locations within the commercial district to assess localized thermal responses. This combined approach allows us to evaluate both average and site-specific cooling performance under peak thermal conditions. The overall simulation workflow and evaluation process used in this study are shown in Figure 3.

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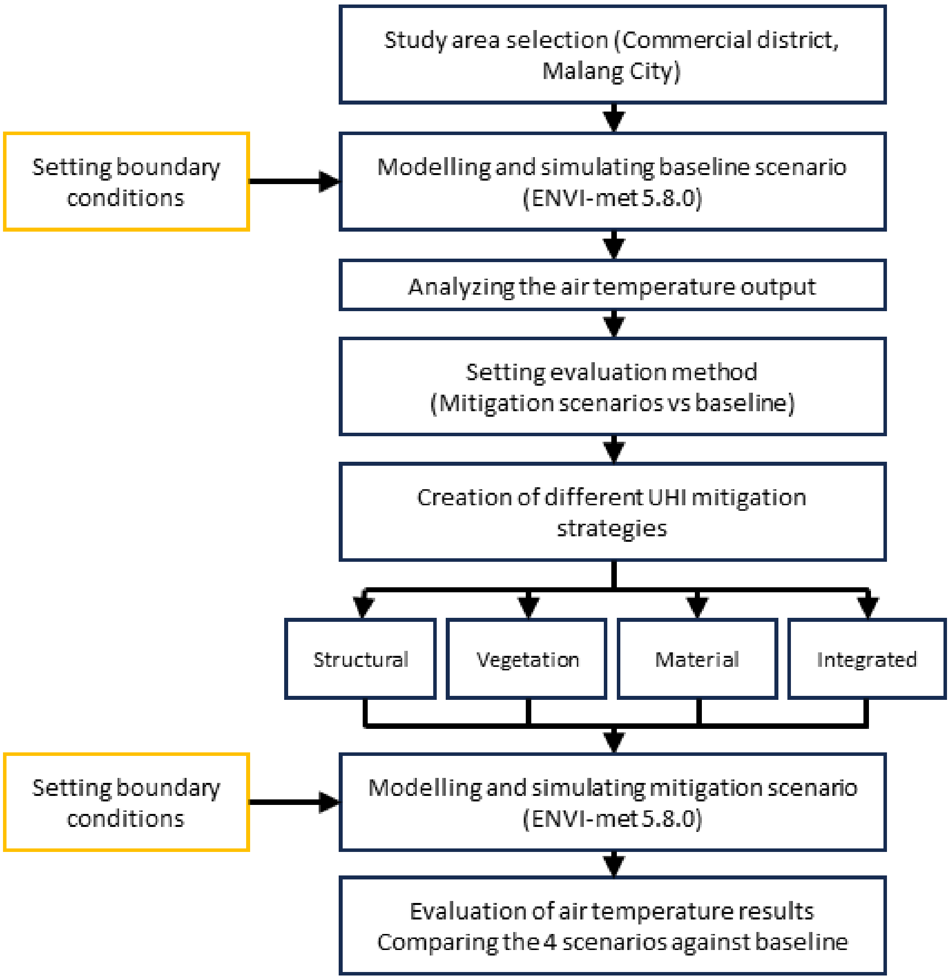

Figure 3. Research framework for the simulation-based evaluation of UHI mitigation strategies using ENVI-met [19].

3. Result and discussion

3.1. Existing air temperature conditions

The existing condition shows the baseline outdoor air temperature for the study area during peak dry-season conditions, without any UHI mitigation measures. Simulation results reveal that outdoor air temperature at pedestrian height (1.4 m) gradually increases from morning to reach its highest point in the early afternoon (Fig. 4). The average maximum air temperature in this condition hits 32.44 °C, showing significant heat buildup during the day in the dense commercial district.

Spatial analysis of air temperature distribution during peak hours reveals limited variation across the study area (Fig. 5). Slightly lower air temperatures occur in shaded areas, while higher temperatures are common in exposed pedestrian paths and open paved surfaces. However, these differences are moderate. This suggests that strong air mixing within the urban canopy layer lessens sharp temperature changes at the neighborhood level. Higher air

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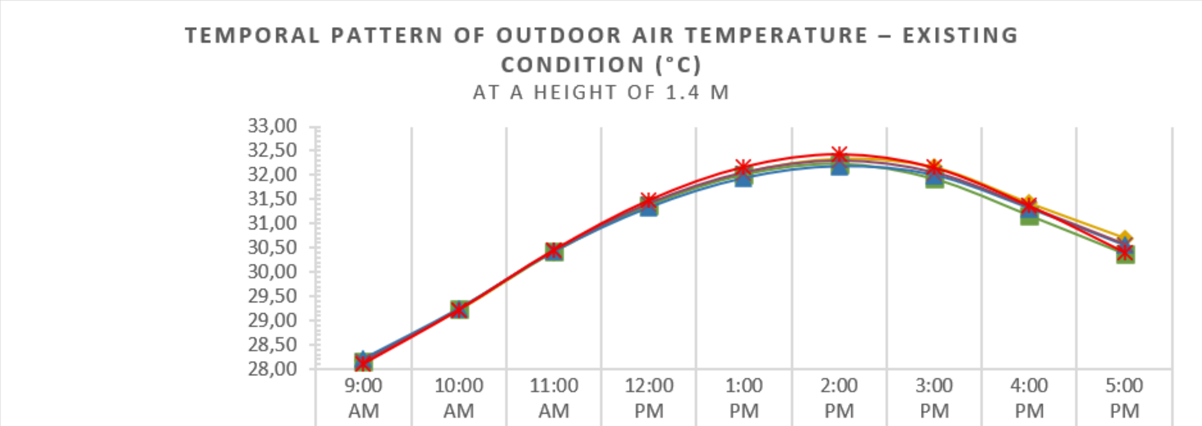
temperatures at the downwind edge are affected by wind forces and boundary-related advection effects in the simulation zone. This reflects how sensitive ENVI-met air temperature fields are to the wind conditions used.



	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM	5:00 PM
Receptor 1 (178,56)	28,18	29,20	30,41	31,38	32,05	32,34	32,16	31,42	30,70
Receptor 2 (99,31)	28,17	29,24	30,42	31,39	32,01	32,24	31,92	31,17	30,38
Receptor 3 (42,90)	28,22	29,25	30,42	31,33	31,93	32,18	31,99	31,31	30,55
Receptor 4 (23,62)	28,15	29,21	30,43	31,41	32,05	32,29	32,05	31,33	30,57
Area-average	28,11	29,22	30,46	31,49	32,18	32,44	32,16	31,37	30,41

Figure 4. Temporal variation of outdoor air temperature at pedestrian height (1.4 m) under existing conditions.

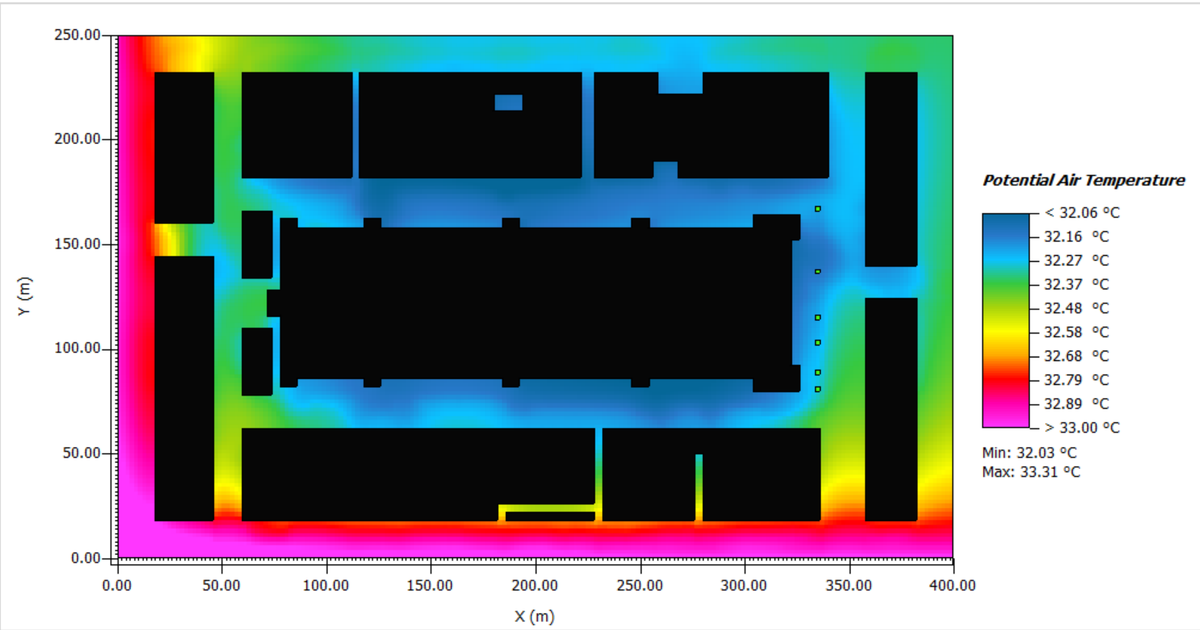


Figure 5. Spatial distribution of outdoor air temperature at pedestrian height (1.4 m) under existing conditions at 14:00.

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Overall, the baseline simulation shows a clear time lag between solar noon and the highest outdoor air temperature. The peak outdoor air temperature occurs around 14:00, while solar noon in Malang City is at approximately 11:15. This results in a lag of nearly 3 hours. This delay aligns with earlier studies that found near-surface air temperature usually peaks several hours after solar noon due to indirect heating from urban surfaces [20]. In the study area, hard surfaces with low reflectivity absorb heat during midday. They also slowly release that heat to the surrounding air through conduction and convection, keeping air temperatures high in the early afternoon. However, even with different shading conditions between the more sheltered central parts and the more exposed western edges of the study area, the temperature differences remain fairly small. This uniformity in air temperature suggests effective mixing within the urban canopy. Lateral movement and turbulent diffusion continually redistribute air and limit localized temperature changes [21]. From the air temperature standpoint, the baseline condition shows consistently high and uniform daytime air temperatures across the commercial district. This indicates the existing urban setup has a limited cooling effect, making the area highly vulnerable to daytime heat exposure. This finding serves as a key reference for assessing the effectiveness of UHI mitigation strategies.

3.2. Effects of UHI mitigation scenarios on outdoor air temperature

The patterns of area-averaged outdoor air temperature show that all mitigation scenarios have a similar daily trend to the current condition. There is a gradual increase in temperature from the morning, with a peak in the early afternoon (Fig. 6). This steady pattern indicates that the mitigation strategies do not change when maximum air temperature occurs but mainly affect its intensity.

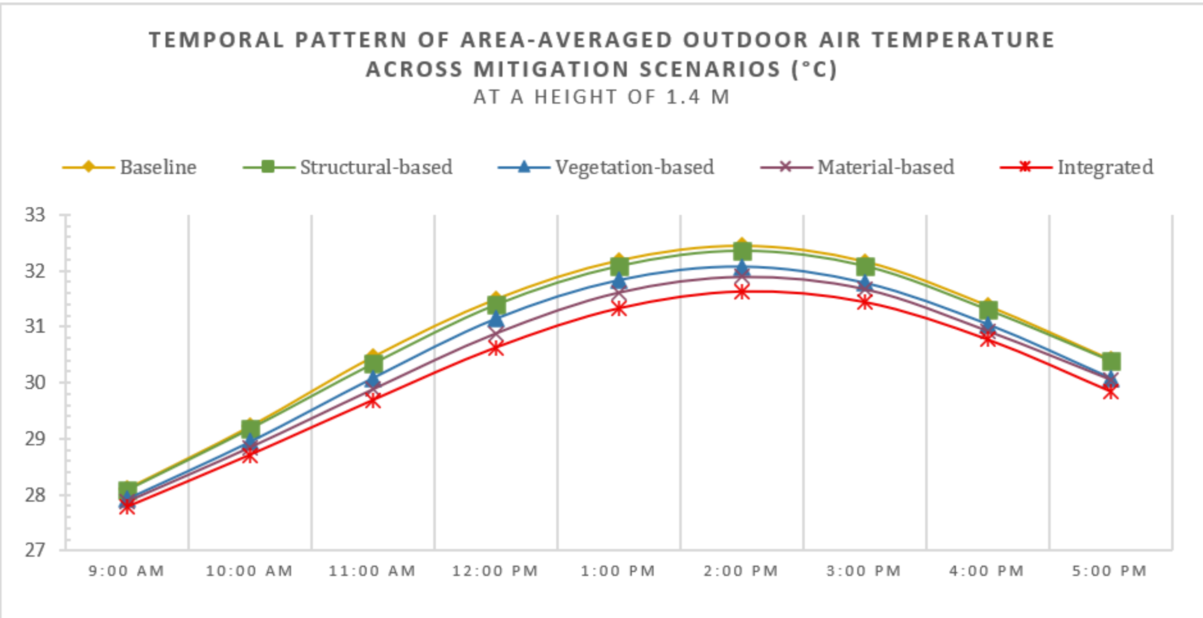

Figure 6. Temporal pattern of area-averaged outdoor air temperature across mitigation scenarios at a height of 1.4 m.

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Relative to the baseline condition, all mitigation scenarios result in lower outdoor air temperatures throughout the daytime period, although the magnitude of reduction varies among strategies (Fig. 7).

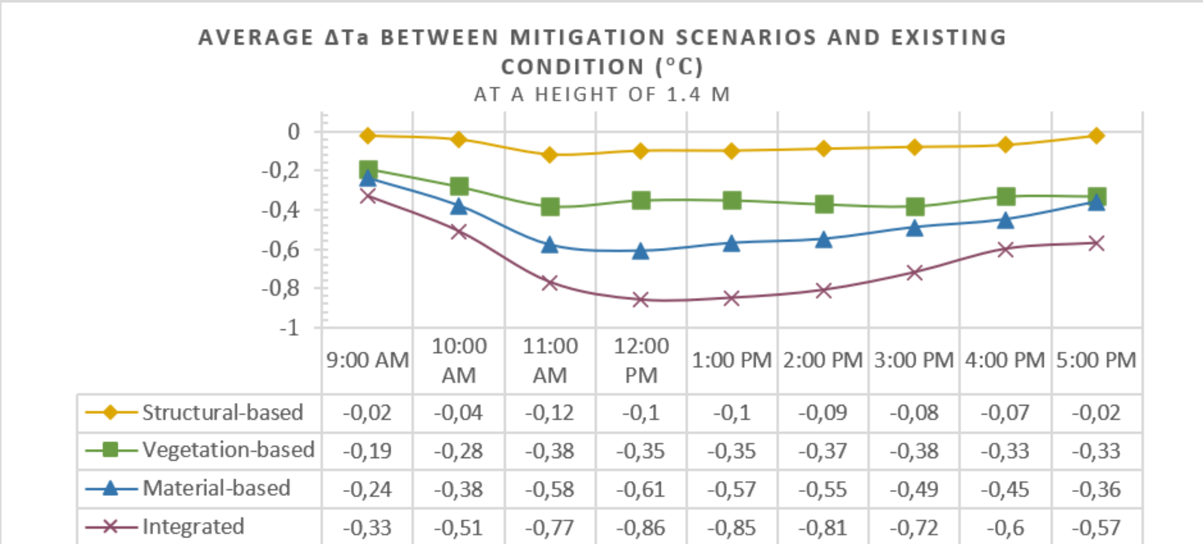

Figure 7. Temporal variation of air temperature changes (ΔT_a) relative to the existing condition.

The structural-based intervention shows the smallest effect, with a maximum average air temperature reduction of 0.12 °C. The vegetation-based intervention offers a greater cooling benefit, reaching a maximum reduction of about 0.38 °C. The material-based intervention achieves a higher maximum reduction of 0.61 °C. The integrated intervention demonstrates the best performance, producing the largest maximum air temperature reduction of 0.86 °C (Tabel 3).

Table 3. Maximum outdoor air temperature changes relative to the existing condition at receptor points and area average.

Max air temp. reduction	Structural-based intervention	Vegetation-based intervention	Material-based intervention	Integrated intervention
Receptor 1	- 0.11 °C	- 0.40 °C	- 0.77 °C	- 1.01 °C
Receptor 2	- 0.14 °C	- 0.51 °C	- 0.72 °C	- 1.01 °C
Receptor 3	- 0.15 °C	- 0.53 °C	- 0.74 °C	- 1.02 °C
Receptor 4	- 0.12 °C	- 0.46 °C	- 0.67 °C	- 0.94 °C
Average	- 0.12 °C	- 0.38 °C	- 0.61 °C	- 0.86 °C

The spatial distribution of outdoor air temperature at peak conditions (14:00) shows that the differences among mitigation scenarios are relatively small at the district level (Fig. 8). Structural interventions create localized cooling in shaded areas; however, this effect does not

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significantly change the overall air temperature pattern. Likewise, scenarios based on vegetation, materials, and integrated approaches do not generate strong spatial contrasts. Instead, reductions in air temperature are spread fairly evenly across the study area. This indicates that air mixing within the urban canopy layer largely influences the spatial air temperature response. As a result, there is only a slight variation, even with different mitigation strategies in place.

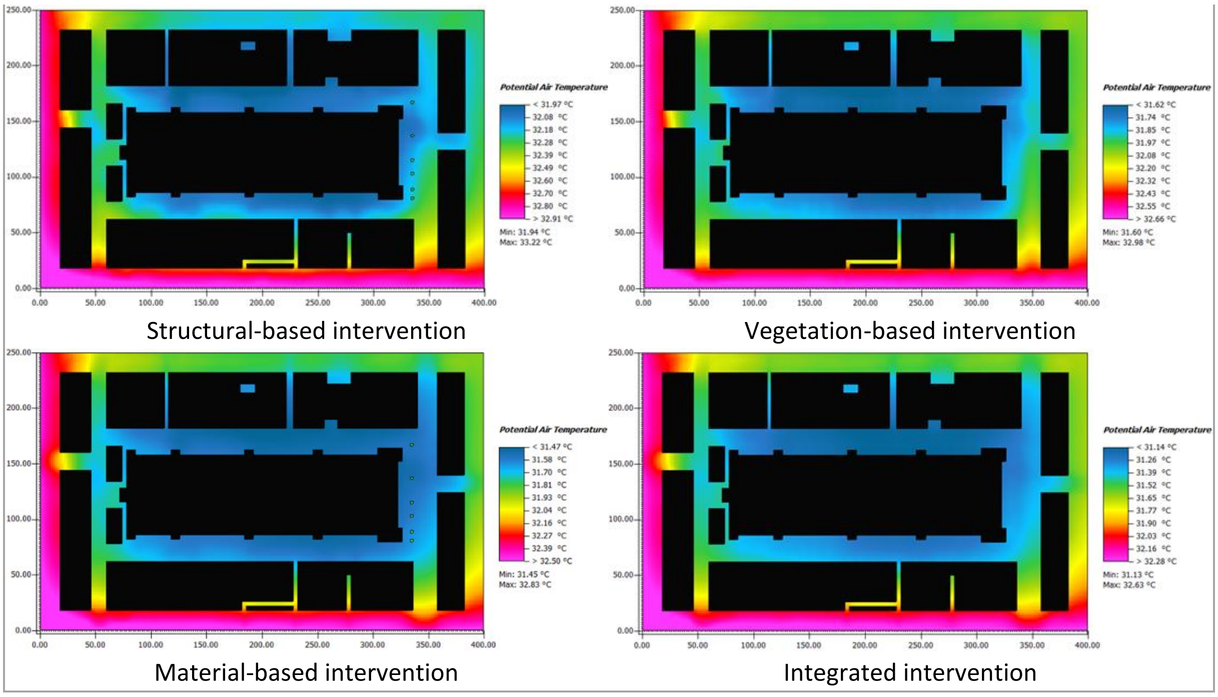

Figure 8. Spatial patterns of outdoor air temperature at pedestrian height (1.4 m) at 14:00 showing limited spatial differentiation across UHI mitigation scenarios.

The different mitigation scenarios examined in this study affect outdoor air temperature through specific physical mechanisms that work on the urban surface and atmosphere energy exchange. Structural interventions mainly reduce direct solar exposure by providing localized shading. However, the fragmented and limited shadow coverage does not significantly change the overall urban heat balance. This results in only minor reductions in air temperature at the district level. Vegetation-based interventions are more successful in moderating air temperature. They combine radiative shading with evapotranspiration, allowing a large portion of the absorbed solar energy to turn into latent heat. This process reduces the sensible heat transfer from urban surfaces to the air above [22,23]. Material-based interventions lower outdoor air temperature by increasing surface albedo and minimizing heat absorption at the surface-air interface [24]. Yet, in dense urban settings, highly reflective materials can cause multiple shortwave reflections within the urban canyon. This could raise the mean radiant temperature at pedestrian level, even if air temperatures are lower [25]. Additionally, higher surface reflectivity may lead to visual discomfort and glare, which is a key limitation when assessing material-based approaches based solely on air temperature performance [26]. The

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integrated intervention achieves the greatest reduction in air temperature by simultaneously suppressing radiative heat gains, enhancing latent heat flux, and reducing surface heat storage, while vegetation and shading elements help mitigate the radiative side effects associated with reflective materials. These interactions show that while all strategies help lower air temperature, their effects on heat differ based on how they change radiative, convective, and latent heat processes. Therefore, although this study offers a solid evaluation of mitigation effectiveness related to outdoor air temperature, a full assessment of human thermal comfort is necessary to completely understand the thermal performance of each strategy at the pedestrian level.

4. Conclusions

This study evaluated how effective physical strategies are in reducing outdoor air temperature in a dense tropical commercial area during peak dry-season conditions through ENVI-met simulations. The results indicate that these strategies mainly lower outdoor air temperatures during the day, while the overall daily pattern and timing of the temperature peak stay mostly the same. Structural-based intervention reduces direct solar exposure through localized shading, but its fragmented and limited coverage results in only minor air temperature reductions, with a maximum average reduction of 0.12 °C. Vegetation-based intervention provides moderate cooling through shading and evapotranspiration processes, achieving a maximum average reduction of 0.38 °C. Material-based intervention achieved greater cooling by increasing surface reflectivity, reaching a maximum average reduction of 0.61 °C, although it comes with trade-offs related to radiative effects. The integrated intervention demonstrates the most effective performance in improving outdoor thermal conditions at the pedestrian level, producing the largest maximum average air temperature reduction of 0.86 °C. By focusing on extreme heat during the hottest part of the dry season period instead of average climatic conditions, this study boosts UHI research in tropical settings. It also makes simulation-based evaluations more relevant for climate-sensitive urban design in commercial areas. The findings emphasize the importance of integrated strategies as effective ways to reduce daytime heat exposure in tropical cities. Future research should build on this work by exploring various seasonal conditions, different urban designs, and real-world validation. It should also include human thermal comfort indicators to fully assess how reductions in air temperature and radiative exposure impact pedestrians.

Authors Contributions

M.H. conceived the study, designed the research methodology, conducted the ENVI-met simulations, analysed the data, created the figures, and drafted the manuscript. R.W. co-conceived the study, provided methodological guidance, and supervised the research process. N.A. contributed to the research design and participated in the interpretation of the results. P.T. assisted in data interpretation and provided critical input on the research analysis. E.L.W. contributed to reviewing and editing the manuscript. All authors contributed to the discussion of the results and revisions of the manuscript. All authors approved the final version of the manuscript and agree to be accountable for the content of the work.

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