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Outdoor thermal comfort performance in urban heat island mitigation: A Simulation-Based assessment in a commercial district using ENVI-met

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ABSTRACT

Outdoor thermal discomfort in commercial districts presents a critical challenge in tropical urban environments, where elevated air temperatures and intense solar radiation limit the usability and comfort of open spaces. This study evaluates the effectiveness of Urban Heat Island (UHI) mitigation strategies in enhancing outdoor thermal comfort within a commercial district through ENVI-met simulations. Four intervention scenarios were developed and compared against existing conditions, encompassing structural-based, vegetation-based, surface material–based, and integrated approaches. Simulations were conducted for the hottest day of the dry season, with thermal comfort assessed at pedestrian height (1.4 m) using the Physiological Equivalent Temperature (PET) index. Structural interventions produced an average PET reduction of 1.24 K, demonstrating localized cooling effects, whereas vegetation-oriented strategies achieved the most substantial improvement, reducing average PET by up to 3.91 K. In contrast, material-based interventions exhibited the least efficacy, yielding a maximum average PET reduction of only 0.32 K and even contributing to increased PET during daytime hours due to reflected solar radiation. The combined intervention scenario delivered a more balanced outcome, with average PET reductions reaching 2.60 K. Despite these interventions, PET values largely remained within the "very hot" category, underscoring the necessity for radiation-sensitive urban design approaches that prioritize vegetation-centric mitigation strategies.

Introduction

In many cities, particularly within tropical regions, rapid urbanization and intensified commercial land use have exacerbated the Urban Heat Island (UHI) phenomenon. Commercial zones are typically characterized by high building densities and extensive impervious surfaces, punctuated only by small-scale vegetation, which serve as strong indicators of elevated surface temperatures and UHI effects, as previously documented in the literature (Bečić and Gašparović 2025). Outdoor Thermal Comfort (OTC) deteriorates progressively with increasing UHI intensity, primarily due to elevated air temperatures and prolonged exposure to heat (Ren et al. 2023). Numerous studies have demonstrated that commercial districts experience greater thermal stress than surrounding areas, with asphalt-dominated streets reaching extreme surface temperatures and producing severe discomfort at the pedestrian scale (Sartina et al. 2023; Widastri, Hasyim, and Agustin 2025). These conditions constrain the usability of outdoor spaces and pose significant health risks, emphasizing the urgent need for effective UHI mitigation strategies in commercial environments.

Several approaches have been proposed to attenuate outdoor heat and thermal stress, including structural modifications, vegetative interventions, and alterations to surface morphology (M. Imran et al. 2021). In recent years, numerical microclimate simulations particularly using ENVI-met have become widely employed to evaluate the spatial effectiveness of UHI mitigation strategies, as this tool can simulate key microclimatic variables across diverse urban configurations (Apritasari et al. 2022). evertheless, the majority of existing UHI studies have focused on subtropical cities, with tropical contexts remaining relatively underexplored. Furthermore, mitigation effectiveness is frequently assessed through basic microclimatic parameters such as air temperature, despite evidence indicating that OTC is more strongly influenced by radiative conditions and airflow. Prior research suggests that certain structural or surface-based interventions may reduce air temperature while simultaneously increasing mean radiant temperature, thereby producing limited or even counterproductive effects on thermal comfort (Lopez-Cabeza et al. 2022). This underscores the necessity of human-centered, OTC-based evaluations rather than relying solely on-air temperature metrics.

To address these gaps, this study examines UHI mitigation strategies within a tropical commercial district using ENVI-met simulations. Four intervention scenarios were developed: structural-, vegetation-, and material-based strategies, as well as a combined approach. These scenarios were compared with existing conditions, focusing on the hottest day of the dry season, with OTC evaluated at pedestrian height. From an academic perspective, the study provides empirical evidence for a more nuanced understanding of the relative performance of different mitigation strategies in alignment with human thermal response. Practically, the findings offer an evidence base for climate-responsive urban design aimed at enhancing the thermal comfort of outdoor spaces within tropical commercial districts.

Methods

Study area

The research area is situated within the Pasar Besar Malang commercial district, encompassing the main market building and the surrounding retail blocks (figure 1). This location was deliberately selected as a representative core commercial zone with high UHI potential. Previous studies have identified micro-scale UHI effects within this corridor, with road surfaces emerging as thermal hotspots, reaching surface temperatures of up to 48.62 °C (Widastri, Hasyim, and Agustin 2025).

Figure 1. Location and placement of the study area

Microclimatic Modeling with ENVI-met

This study employed ENVI-met (version 5.8.0) as a numerical simulation tool to evaluate outdoor thermal comfort (OTC) mitigation strategies. ENVI-met is a three-dimensional microclimate model designed to simulate interactions among the atmosphere, buildings, vegetation, and ground surfaces at the local urban scale. It applies a Computational Fluid Dynamics (CFD) approach based on Reynolds-Averaged Navier–Stokes (RANS) equations to model atmospheric flow, turbulence, and heat transfer processes (Banerjee et al. 2024; Mandjoupa et al. 2025). Validation studies indicate that ENVI-met reliably captures temporal variability in key microclimatic variables and outdoor thermal comfort indices, despite some known limitations in wind speed simulation (Elraouf et al. 2022; Lefevre et al. 2025). Consequently, ENVI-met is considered appropriate for comparative assessment of OTC mitigation scenarios in this study.

A uniform horizontal and vertical grid resolution of 2 × 2 × 2 m was applied, as this resolution effectively captures urban microclimatic heterogeneity while maintaining computational efficiency (Forouzandeh 2018). The three-dimensional model was developed using spatial data from Google Earth, field observations, and visual interpretation of existing urban features. To accurately represent urban geometry within the ENVI-met grid, the simulation domain was rotated 70° clockwise relative to true north. Detailed domain configuration, grid structure, and nesting parameters are presented in table 1.

Table 1. Parameters of the 3D model domain

Parameter	Value
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)

Simulations represented a full diurnal heating cycle on the hottest day of the 2024 dry season, using a uniform simple-forcing meteorological configuration across all scenarios. Hourly meteorological data were obtained from the Worldweather.info portal, while the hottest day selection and maximum air temperature validation were based on official records from the BMKG online portal. Wind speed was set to 0.1 m/s to simulate weak wind conditions and minimize external atmospheric influence. Each simulation ran for 12 hours, with only the first 3 hours of output discarded to account for spin-up effects (Forouzandeh 2018; Mebarki et al. 2022). Detailed input parameters for the ENVI-met setup are provided in table 2.

Table 2. Input Parameters used to Initialize the ENVI-met simulation

Category	Value
Start time	5:00 local time
Total Simulation	12 h
Boundary condition	simple Forcing
Winds peed 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%

UHI mitigation scenario development

UHI mitigation strategies are generally categorized according to their physical mechanisms: structural-based, vegetation-based, material-based, and anthropogenic heat reduction (M. Imran et al. 2021). Structural-based interventions modify urban form to influence solar access and radiative exposure. Vegetation-based measures reduce urban heat through shading and evapotranspiration, with studies in tropical cities showing tree-filled areas experience air temperature reductions of approximately 1–2 °C, with localized cooling exceeding 3 °C (Aini et al. 2025). Material-based strategies aim to alter the radiative and thermal properties of urban surfaces, while anthropogenic heat reduction involves lowering heat emissions from human activities. For this study, the focus is on physical, space-based interventions: structural, vegetation, and surface material modifications. Anthropogenic heat reduction was excluded due to its limited controllability within spatial design. The configuration of each mitigation scenario is illustrated in figure 2 and summarized in table 3. All scenarios were simulated under identical modeling, meteorological, and numerical conditions to ensure that observed microclimatic and OTC differences resulted solely from the applied interventions.

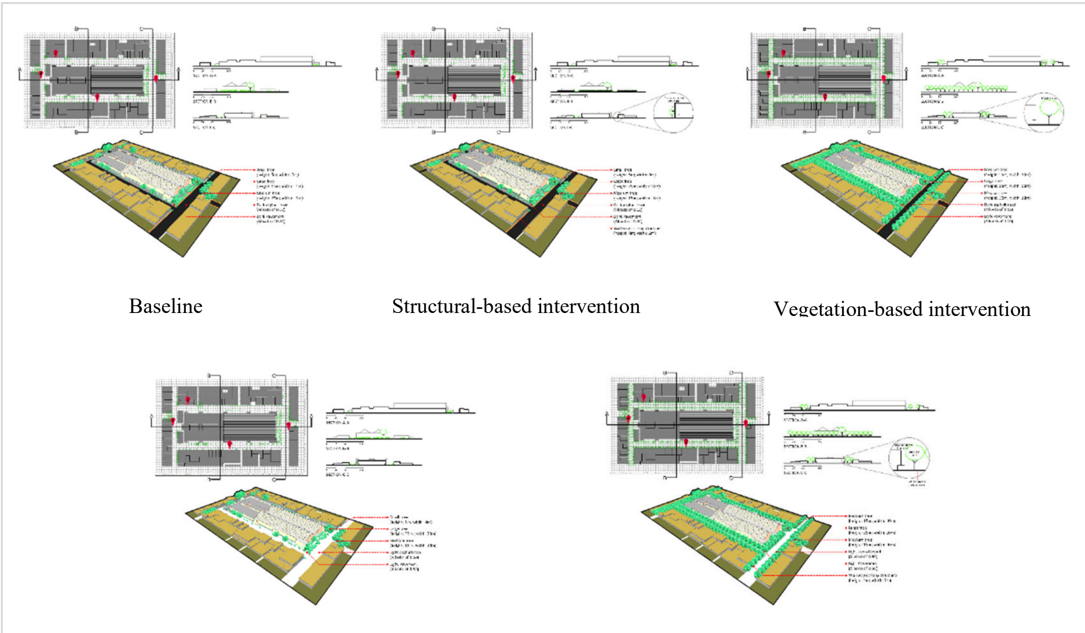


Figure 2. Spatial configuration of the baseline condition and UHI mitigation scenarios

Table 3. Input parameters used to Initialize the ENVI-met simulation

Scenario	Description
Baseline	Represents the existing urban condition without any modification to buildings, vegetation, or surface materials, serving as the reference scenario for comparison.
Structural-based intervention	Introduces continuous concrete canopies with a width of approximately 2 m, installed at a height of 4 m above ground level along pedestrian corridors and aligned with building façades, to reduce sky view factor and direct solar radiation at pedestrian level.
Vegetation-based intervention	Enhances vegetation by replacing small trees with medium-sized street trees (~15 m height) and adding them at 10 m intervals along pedestrian corridors, retaining existing medium and large trees to improve shading and evapotranspiration.
Material-based intervention	Modifies hard surfaces by replacing low-albedo asphalt (0.12) and dark pavements (0.2) with high-albedo asphalt (0.59) and concrete pavements (0.5) to reduce solar heat absorption.
Integrated intervention	Combines structural shading (2 m wide canopies at 4 m height), vegetation enhancement using medium-sized street trees, and high-albedo surface materials simultaneously, allowing the synergistic effects of reduced radiative exposure, increased evapotranspiration, and lower surface heat storage to be evaluated.

Assessment of thermal comfort

OTC is a critical factor in urban open-space design, determining human thermal comfort in outdoor environments (Binarti and Koerniawan 2023). Numerous thermal comfort indices exist, with their applicability dependent on the chosen modeling framework. Among 165 indices evaluated, only PET, PTJ, PST, and UTCI are suitable for obstacle-resolving meteorology models such as ENVI-met (Fischereit and Schlünzen 2018). PET is the most widely applied, facilitating comparisons across studies and climatic zones.

PET is based on the human heat balance model, quantifying outdoor thermal conditions by integrating air temperature, humidity, wind speed, and short- and long-wave radiation into an equivalent air temperature (°C) (Höppe 1999). In this study, PET values were computed using the BIO-Met module within ENVI-met and extracted at pedestrian height (1.4 m) to represent human thermal exposure. PET analysis was conducted at two spatial scales: area-average and four purposively selected receptor points representing typical pedestrian environments. Given regional physiological and behavioral adaptation, PET comfort ranges differ across climates; thus, tropical-adjusted ranges were used in this study (table 4).

Table 4. PET thermal comfort ranges for tropical climates

PET (°C)	Thermal sensation
< 23.0	Slightly cool
23.0 – 34.7	Comfortable
34.7 – 37.6	Slightly Hot
37.6 – 43.4	Hot
⩾ 43.4	Very Hot

Source: Ribeiro et al., 2022

Framework of the research

The study follows a simulation-based workflow using ENVI-met (figure 3), starting with preparation of spatial and meteorological inputs representing existing conditions, followed by microclimatic modeling. OTC was evaluated by computing PET using the BIO-Met module, assuming a standard human subject (default male) with average clothing insulation. The performance of each mitigation strategy was quantified through PET differences (ΔPET = PET_intervention – PET_existing), providing an objective measure of improvement relative to the baseline scenario.

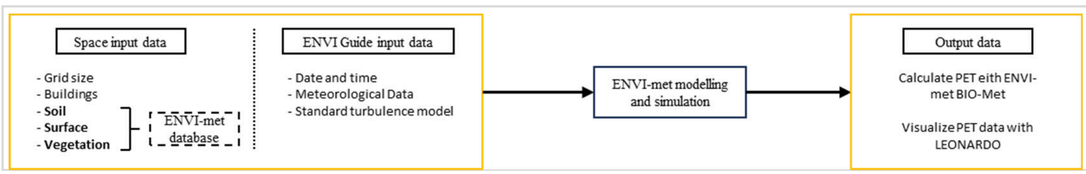


Figure 3. Simulation process for ENVI-met software
Source: Basaly et al. 2021

Results and discussion

Existing thermal comfort conditions

Under current conditions, the study area experiences pronounced thermal stress at pedestrian level, as evidenced by both temporal and spatial variations in PET. Area-averaged PET rises sharply from the morning, peaking at approximately 55.24 °C at 13:00, before gradually declining in the late afternoon (figure 4). Overall, PET remains within the "very hot" thermal stress category between 09:00 and 16:00, indicating persistent outdoor thermal discomfort during peak activity hours. Significant temporal fluctuations are observed across receptor points, reflecting strong spatial heterogeneity in thermal comfort. At Point 1, PET declines sharply from 57.45 °C at 15:00 to 38.52 °C at 16:00, transitioning rapidly from "very hot" to "hot" conditions. Point 2 exhibits a sudden increase in PET from 39.94 °C at 10:00 to 56.40 °C at 11:00. Point 3 experiences extremely high PET values in the morning (57.76 °C at 09:00) followed by a sharp decrease between 11:00 and 12:00. Point 4 shows a similar abrupt drop from 55.78 °C at 12:00 to 42.62 °C at 13:00. These large, sudden variations highlight the highly dynamic and location-dependent nature of outdoor thermal comfort in the existing urban environment (figure 5).

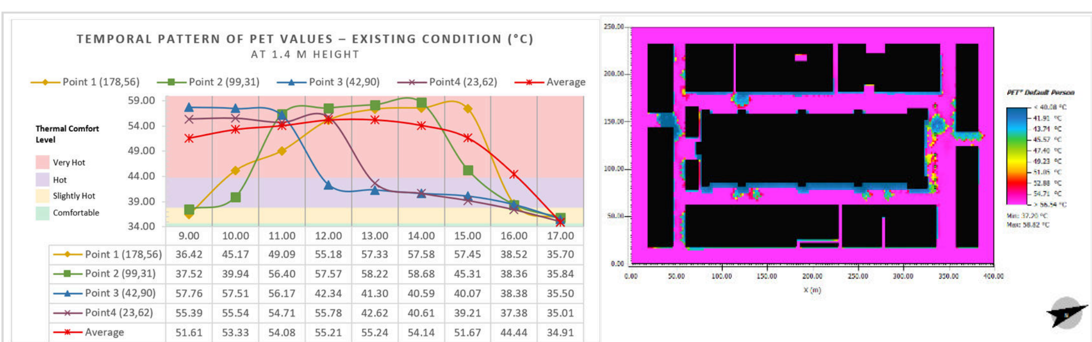


Figure 4. Temporal variation and spatial distribution of PET under existing conditions at pedestrian level (1.4 m)

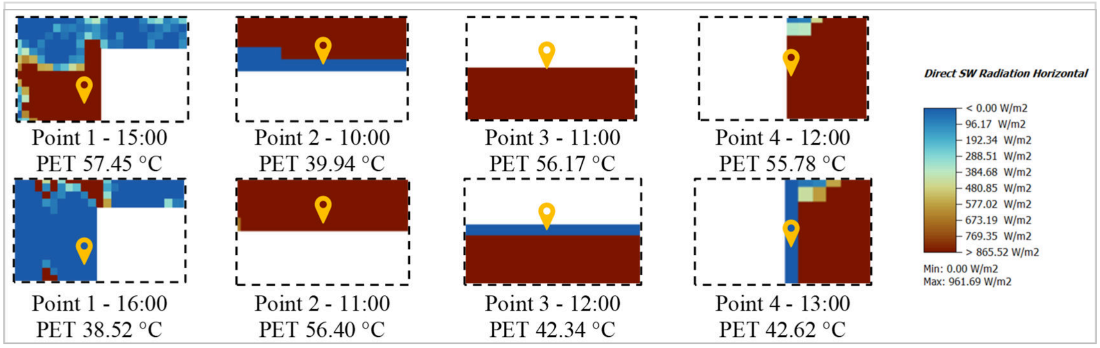
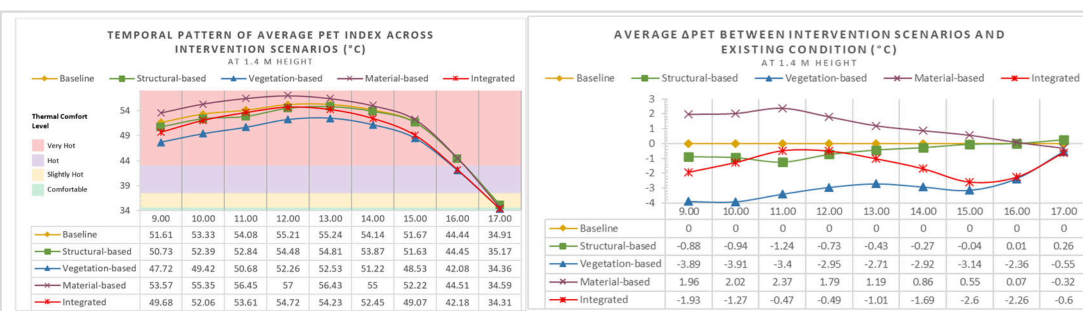


Figure 5. Insets showing the spatial distribution of solar radiation exposure and shading at selected receptor points

The spatial distribution of Physiologically Equivalent Temperature (PET) at 13:00, corresponding to the period of maximum thermal stress, reveals extensive zones of extreme heat stress across unshaded and open areas, particularly along major street corridors. Peak PET values reach approximately 58.82 °C, whereas lower PET values are confined to regions benefiting from shading provided by buildings or tree canopies.

Effectiveness of UHI mitigation scenarios

The efficacy of urban heat island (UHI) mitigation strategies was assessed by comparing temporal PET variations at pedestrian height under existing conditions with those under structural, vegetation, material, and integrated-intervention scenarios. Results indicate distinct differences in the magnitude of PET reduction across strategies (figure 6). The structural-based intervention yields a modest area-wide improvement, with an area-average PET reduction of −1.24 K. Nevertheless, pronounced localized cooling occurs at receptor points, where maximum PET reductions range from −12.66 K to −16.72 K during peak daytime hours. This suggests that structural shading is effective in alleviating heat hazards at specific pedestrian locations; however, its impact on area-average conditions is limited due to the spatially constrained nature of its effect. Similar scale-dependent shading effects have been documented in recent studies, demonstrating that shading substantially influences mean radiant temperature at the microscale while producing only minor changes when averaged over larger urban domains (Wilson et al. 2025).



	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00
Baseline	51.61	53.33	54.08	55.21	55.24	54.14	51.67	44.44	34.91
Structural-based	50.73	52.39	52.84	54.48	54.81	53.87	51.63	44.45	35.17
Vegetation-based	47.72	49.42	50.68	52.26	52.53	51.22	48.53	42.08	34.36
Material-based	53.57	55.35	56.45	57	56.43	55	52.22	44.51	34.59
Integrated	49.68	52.06	53.61	54.72	54.23	52.45	49.07	42.18	34.31

	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00
Baseline	0	0	0	0	0	0	0	0	0
Structural-based	-0.88	-0.94	-1.24	-0.73	-0.43	-0.27	-0.04	0.01	0.26
Vegetation-based	-3.89	-3.91	-3.4	-2.95	-2.71	-2.92	-3.14	-2.36	-0.55
Material-based	1.96	2.02	2.37	1.79	1.19	0.86	0.55	0.07	-0.32
Integrated	-1.93	-1.27	-0.47	-0.49	-1.01	-1.69	-2.6	-2.26	-0.6

Figure 6. Temporal variation of average PET and corresponding ΔPET values across mitigation scenarios at pedestrian level (1.4 m)

In contrast, the vegetation-based intervention demonstrates the highest overall effectiveness among individual mitigation strategies. The area-averaged PET reduction reaches −3.91 K, accompanied by substantial PET decreases across all four receptor points, with maximum reductions ranging from −11.80 K to −16.22 K. Unlike structural shading, vegetation provides both localized and spatially continuous cooling, achieved through the combined effects of canopy shading and evapotranspiration (Yin et al. 2024). The most pronounced PET reduction occurs during the morning, when low-angle solar radiation is effectively intercepted by tree canopies, and high stomatal conductance facilitates efficient transpiration. Toward midday, however, increasing vapor pressure deficit induces partial stomatal closure, moderating the cooling effect despite higher solar irradiance (Meili et al. 2021).

The material-based intervention exhibits limited and temporally inconsistent effectiveness. PET values rise from morning to midday due to enhanced shortwave radiation reflected from high-albedo surfaces, then decrease toward late afternoon as incoming solar radiation diminishes. This pattern aligns with previous research indicating that increasing surface albedo primarily alters mean radiant temperature, a dominant component in PET formation (PRON and ZYANE 2025).

The integrated intervention, which combines structural, vegetation, and material-based measures, achieves a more balanced improvement in outdoor thermal comfort; nonetheless, reflected radiation effects are not entirely mitigated. The area-averaged PET decreases by −2.60 K, while significant local cooling is observed at select receptor points, with maximum reductions between −11.72 K and −17.77 K. Consequently, although the integrated scenario provides relatively homogeneous PET reductions, residual reflected radiation explains why its cooling performance does not fully match the potential achieved by the triple vegetation layer alone during periods of high solar input.

Table 5. Maximum PET reduction under different UHI mitigation scenarios

Max PET reduction on	Structural-based intervention		Vegetation-based intervention		Material-based intervention		Integrated intervention	
Point 1	- 12.66 K	13:00	- 11.80 K	12:00	- 0.38 K	17:00	- 11.72 K	12:00
Point 2	- 13.81 K	12:00	- 14.21 K	13:00	- 0.06 K	17:00	- 13.68 K	11:00
Point 3	- 13.15 K	11:00	- 15.09 K	10:00	- 0.20 K	17:00	- 12.76 K	11:00
Point 4	- 16.72 K	9:00	- 16.22 K	9:00	- 0.35 K	17:00	- 17.77 K	9:00
Average	- 1.24 K	11:00	- 3.91 K	10:00	- 0.32 K	17:00	- 2.60 K	15:00

Conclusions

This study investigated the potential of various UHI mitigation strategies to enhance outdoor thermal comfort (OTC) in a dense commercial district of Malang, using ENVI-met–based microclimatic simulations. The findings indicate that the existing urban landscape induces chronically high thermal stress at pedestrian level, primarily due to excessive interception of solar radiation during daytime. Despite the implementation of mitigation scenarios and their influence on local microclimatic conditions, simulated PET levels predominantly fall within thermal discomfort categories for most periods, suggesting that pedestrians would generally experience thermal stress even under mitigations.

Comparative evaluation of the strategies reveals that vegetation-based interventions provide the most consistent improvement in OTC through the synergistic effects of shading and evapotranspiration. Structural interventions mainly offer localized relief in shaded pedestrian areas. Material-based strategies display limited and temporally variable performance, especially during periods of high solar radiation, whereas integrated strategies achieve more balanced improvements but cannot fully eliminate residual radiative effects. Overall, these results underscore that effective UHI mitigation in tropical commercial settings relies on design approaches emphasizing radiative control, particularly via vegetation, complemented by structural measures, while material-based interventions require careful application due to complex radiative interactions. PET-based simulation evaluation further provides a robust framework for guiding climate-responsive urban design and planning.

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Author(s) contribution

Miftahul Huda contributed to the research concepts preparation, methodologies, investigations, data analysis, visualization, articles drafting and revisions.

Respati Wikantiyoso contribute to the research concepts preparation and literature reviews, data analysis, of article drafts preparation and validation.

Nurul Aini, Pindo Tutuko contribute to methodology, supervision, and validation.

Erna Winansih contribute to methodology, supervision, and validation.

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