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The Effectiveness of Micro-Scale Urban Green Spaces (Micro-UGS) in Mitigating Urban Heat Island Effects and Enhancing Residents' Thermal Comfort in Semi-Public Areas of Vertical Housing in Jakarta

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A B S T R A C T

The Urban Heat Island (UHI) phenomenon in Jakarta significantly elevates temperatures within the built environment, particularly in vertical housing sectors, leading to a decline in residents' thermal comfort. While micro-urban green spaces (UGS) in middle-class apartments serve as potential heat-adaptive elements, empirical studies on their effectiveness in semi-public areas remain limited. This study aims to analyze the correlation between vegetation canopy coverage and Physiological Equivalent Temperature (PET) in the semi-public spaces of Transpark Apartment, Cibubur. Using a mixed-methods sequential explanatory approach, the research analyzed canopy coverage across 12 measurement plots using 180° hemispherical photography and ImageJ software. Microclimate parameters were recorded during peak heat hours to calculate PET, while resident perceptions were gathered from 58 respondents to triangulate objective findings. Results demonstrate a strong inverse correlation (R^2>0.85) between canopy density and PET. Specifically, areas with high canopy coverage (75.08%) achieved a PET of 31.2°C—falling within the tropical comfort zone—while areas with lower coverage (57.15%) remained uncomfortably hot at 36.4°C. The findings indicate that increasing canopy coverage from 57% to 75% can reduce PET by 5.2°C, making UGS Mikro 4.8 times more effective for physiological cooling than city-scale greening. The study recommends a minimum canopy target of 70–75% for vertical housing developments to create effective thermal refuges, supporting Sustainable Development Goals (SDGs) 3, 11, and 13.

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1. INTRODUCTION

The rapid pace of global urbanization has catalyzed the phenomenon known as the Urban Heat Island (UHI), where metropolitan areas experience significantly higher temperatures than their rural surroundings. In the context of Jakarta, Indonesia, this thermal anomaly is exacerbated by high-density built environments, the replacement of natural surfaces with heat-absorbing materials like concrete and asphalt, and a significant deficit in green open spaces (Rizki et al., 2024). This thermal stress directly impacts the energy consumption for cooling and, more critically, the health and well-being of urban residents (Beatley, 2016; Santamouris, 2020). As the city continues to expand vertically, the microclimate within high-rise residential complexes—specifically semi-public spaces—becomes a vital area of study for climate-resilient architecture(Putri & Subekti Ir, n.d.)

Vertical housing projects, such as the Transpark Apartment in Cibubur, often feature communal areas that are intended to serve as social hubs. However, without adequate thermal intervention, these spaces frequently fail to achieve their functional purpose due to extreme outdoor heat (Rizki et al., 2024b). One of the most effective nature-based solutions for mitigating micro-UHI is the strategic implementation of Urban Green Spaces (UGS). Trees and vegetation contribute to cooling through two primary mechanisms: shading, which blocks short-wave solar radiation, and evapotranspiration, which converts sensible heat into latent heat (Zijlema et al., 2020).

Among various thermal indices, the Physiological Equivalent Temperature (PET) has emerged as a reliable indicator for assessing outdoor thermal comfort in tropical climates, as it accounts for both environmental variables and human physiological parameters(Saputri et al., 2023). Recent studies suggest that the morphology of the tree canopy—specifically the percentage of canopy coverage plays a more dominant role in reducing PET than just the presence of ground-level grass or shrubs (Estrada-Carmona et al., 2014). For instance, dense canopy structures can reduce local temperatures by as much as 3°C to 5°C compared to unshaded surfaces (Ciftcioglu, 2017)

Despite the recognized benefits of greenery, many vertical housing developments in Indonesia prioritize aesthetic landscaping over functional thermal performance. There is a critical lack of empirical data regarding the precise threshold of canopy coverage required to bring PET levels into the "comfort" range for Indonesians (31.2°C) in semi-public apartment settings. Most existing research focuses on large-scale urban parks, leaving a gap in understanding how "Micro-UGS" within private or semi-public residential boundaries performs (Taleb & Kayed, 2021)

Therefore, this research investigates the influence of canopy coverage on PET levels at Transpark Apartment, Cibubur. By utilizing hemispherical photography and microclimate monitoring, this study seeks to quantify the correlation between canopy density and physiological cooling. The results are expected to provide actionable guidelines for architects and developers to optimize vegetation density, ensuring that semi-public spaces are not merely ornamental but serve as functional thermal refuges for residents, thereby supporting Sustainable Development Goals 11 and 13 (Saputri et al., 2023)

1.2 Literature Review

The Urban Heat Island (UHI) phenomenon is a major consequence of rapid urbanization in tropical cities such as Jakarta, where high building density, extensive impervious surfaces, and vegetation loss contribute to increased urban temperatures. Recent studies indicate that Land Surface Temperature (LST) in East Jakarta can reach up to 33.8 °C in areas with urban green space coverage below 6%, while each 1% increase in green space may reduce surface

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temperature by approximately 0.6 °C (Rizki et al., 2024a). However, most dense urban districts in Jakarta continue to exhibit critically low green space ratios, exacerbating heat stress at both macro and micro scales.

Vertical residential developments, particularly middle-income apartment complexes, have increasingly contributed to urban heat accumulation due to limited provision of green open spaces reported that green space in Jakarta's apartment developments typically accounts for less than 10% of total land area, significantly below the 30% requirement mandated by local regulations (Setiowati et al., n.d.). As a result, semi-public outdoor spaces such as communal gardens and podium-level open areas are often exposed to intense solar radiation and elevated thermal conditions, reducing their usability during daytime (Amzad Rachi et al., 2025).

In response to land constraints, micro-scale Urban Green Space (UGS Micro) has emerged as a practical heat mitigation strategy in dense urban environments. UGS Micro includes small-scale vegetation elements such as trees, shrubs, and ground cover integrated into limited outdoor spaces within residential complexes(Emmanuel & Krüger, 2012). Empirical evidence suggests that even small vegetated areas can substantially reduce local temperatures through shading and evapotranspiration demonstrated that micro-scale vegetation could reduce LST by up to 6.6 °C in compact urban areas, highlighting its effectiveness compared to more technologically intensive solutions such as green walls (Rizki et al., 2024a).

Among vegetation parameters, canopy coverage plays a critical role in regulating outdoor thermal conditions by reducing solar radiation exposure and mean radiant temperature. Dense tree canopies are particularly effective in improving thermal conditions in semi-public spaces, which function as transitional areas between private units and shared facilities (Emmanuel & Krüger, 2012). Previous studies have shown that improved environmental quality in these spaces increases user presence and activity levels (Putri & Subekti Ir, n.d.), underscoring the importance of thermal comfort in space utilization.

Despite growing interest in urban green infrastructure, research integrating canopy coverage analysis with human-scale thermal comfort indices remains limited, particularly in middle-income vertical housing in tropical climates. Most existing studies rely on macro-scale indicators such as LST or NDVI, which do not fully capture thermal conditions experienced by residents. This study addresses this gap by examining the relationship between canopy coverage and Physiological Equivalent Temperature (PET) in semi-public spaces of a middle-income apartment complex, providing empirical evidence for micro-scale, vegetation-based heat mitigation strategies in humid tropical cities.

2. RESEARCH METHODOLOGY

This research employs a Mixed-Methods Sequential Explanatory Design, combining quantitative environmental measurements with qualitative social surveys. The study focuses on 12 observation plots within the semi-public areas of Transpark Apartment, Cibubur because it has a variety of Micro UGS in communal gardens, corridors, and public areas, as well as an average LST of 31.72 °C (Rizki et al., 2024a).

The research was conducted through a structured and sequential methodological framework designed to integrate objective microclimatic measurements with subjective user perceptions. The preparation phase consisted of site identification and reconnaissance, followed by the purposive selection of twelve observation plots representing a range of vegetation densities within the semi-public spaces of the study area. This stage also included the calibration of all measurement instruments to ensure data accuracy and consistency.

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Quantitative data collection focused on microclimate monitoring and canopy analysis. Canopy coverage was assessed by capturing 180° hemispherical photographs at each observation plot at a standardized height of 1.2 meters above ground level, corresponding to the average human standing eye level(Kassagi et al., 2024). Concurrently, key microclimatic parameters were recorded and subsequently used for thermal comfort assessment. Qualitative data collection was conducted through the distribution of structured questionnaires to 58 residents, utilizing a five-point Likert scale to evaluate subjective thermal perception based on the Thermal Sensation Vote (TSV) method. Data analysis involved processing the hemispherical photographs using ImageJ software to calculate precise canopy coverage percentages by converting sky–canopy ratios into pixel-based measurements. Physiological Equivalent Temperature (PET) values were then calculated using the RayMan Pro model, integrating microclimatic variables with human physiological parameters to quantify outdoor thermal stress. In the final synthesis stage, canopy coverage percentages, PET values, and residents' thermal perception responses were systematically correlated to identify patterns and determine the optimal vegetation threshold required to enhance thermal comfort in semi-public spaces of vertical housing.

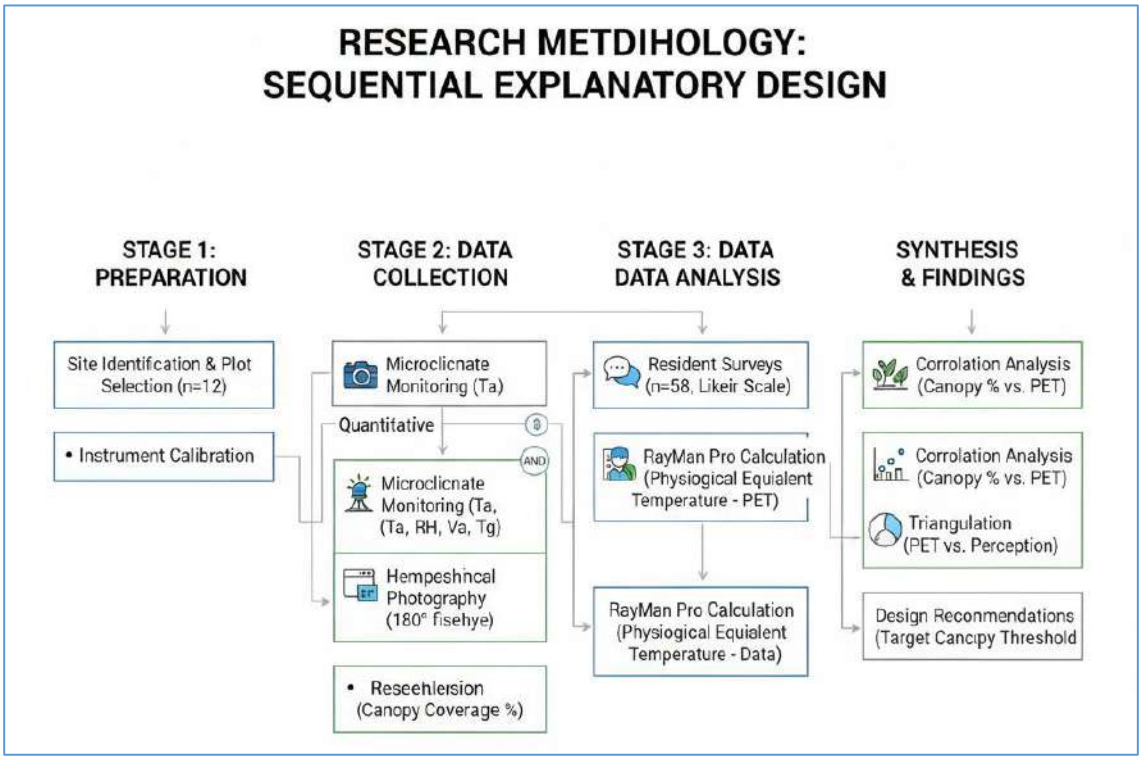

Figure 1 Research Methodology Flow
(Source: Author's Analysis, 2025)

The analytical framework of this study integrates objective microclimatic measurements with subjective human thermal perception to provide a comprehensive assessment of outdoor thermal comfort. Canopy coverage (X) was quantified as the ratio of vegetation foliage to open sky, derived from 180° hemispherical photographs and processed through binary pixel classification using ImageJ software. Thermal comfort (Y) was assessed using the Physiological Equivalent Temperature (PET) index, which integrates key microclimatic variables. PET values, expressed in degrees Celsius (°C), represent the level of physiological thermal strain experienced by the human body under outdoor conditions. Resident perception (Z) was incorporated as a validation variable, using Thermal Sensation Vote (TSV) responses to examine the consistency between objectively calculated PET values and the thermal comfort subjectively experienced by occupants. The integration of these variables enables a triangulated analysis of the relationship between vegetation canopy density, microclimatic thermal conditions, and perceived comfort in semi-public spaces of vertical housing. The core of the methodology is the integration of physical environmental data and human perception.

3. RESULT AND DISCUSSION

The study was conducted at Transpark Cibubur Apartment, a middle-income high-rise residential complex located in Cimanggis District, Depok City, directly adjacent to East Jakarta. As part of a mixed-use development, the complex accommodates residential towers, commercial facilities, and semi-public open spaces that function as daily activity areas for residents. The analysis focused on micro-scale urban green spaces (UGS Micro), particularly semi-public outdoor areas that directly interact with occupants at close range.

Figure 2 Study Location and Research Areas
(Source: Author's Analysis, 2025)

Three semi-public spaces with distinct landscape characteristics were selected as observation zones: the West Communal Garden, the East Communal Garden, and the Swimming Pool Area. These spaces represent typical micro green spaces in middle-income vertical housing, serving social, recreational, and transitional functions. Given the humid tropical climate of the area, with daytime air temperatures commonly ranging between 30–34 °C, these spaces are highly exposed to thermal stress, making them suitable for evaluating the cooling role of vegetation canopy at the microclimatic scale.

Field observations indicated uneven distribution of tree canopy across the site. Several pedestrian paths and seating areas were exposed to direct solar radiation due to limited shading, while other zones benefited from denser tree cover. This spatial heterogeneity provided a suitable basis for examining how variations in canopy coverage influence microclimatic thermal conditions.

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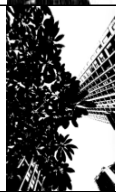
Table 1 Calculation of Canopy Coverage in the West Communal Garden Area

AREA : TAMAN KOMUNAL SISI BARAT						
Plot 1	Image	Hasil Image J	Pixel Canopy	Pixel Total	% Tutupan Canopy	Suhu °C
P1			715151	1191600	60.02	33.9
P2			641485	1267200	50.62	33.6
P3			448606	769680	58.28	33.2
P4			423603	709954	59.67	32.9
% Rata-Rata Tutupan Canopy dan Suhu					**57.15**	**33.40**

(Source: Author's Analysis, 2025)

The West Communal Garden exhibited moderate canopy coverage, ranging from 50.62% to 60.02%, with an average of 57.15%. Vegetation in this area primarily consisted of medium-sized trees with relatively uniform spacing, resulting in partial but discontinuous shading. In contrast, the Swimming Pool Area showed higher and more varied canopy coverage, ranging from 52.75% to approximately 70.00%, with an average of 60.20%. This area combined mature shading trees with open recreational spaces and water surfaces.

Table 2 Calculation of Canopy Coverage in the East Communal Garden Area

AREA : TAMAN KOMUNAL SISI TIMUR						
Plot 2	Image	Hasil Image J	Pixel Canopy	Pixel Total	% Tutupan Canopy	Suhu °C
P5			553308	921600	60.04	32.4
P6			534687	921600	58.02	32.1
P7			645101	921600	70.00	31.7
P8			451595	856080	52.75	31.4
% Rata-Rata Tutupan Canopy Suhu					**60.20**	**31.90**

(Source: Author's Analysis, 2025)

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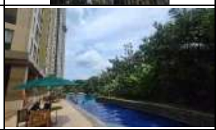
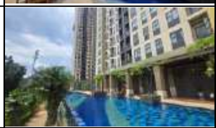
Table 3 Calculation of Canopy Coverage in the Swimming Pool Area

AREA : KOLAM RENANG						
Plot 3	**Image**	**Image J**	**Pixel Canopy**	**Pixel Total**	**% Tutupan Canopy**	**Suhu °C**
P9			628702	1807800	34.78	31
P10			629129	921600	68.26	30.7
P11			1440000	918077	156.85	30.4
P12			921600	536886	171.66	30.1
% Rata-Rata Tutupan Canopy dan Suhu					**107.89**	**30.55**
% Canopy Coverage UGS Mikro dan Suhu					**75.08**	**31.95**

(Source: Author's Analysis, 2025)

The East Communal Garden displayed the highest spatial heterogeneity, with canopy coverage ranging from as low as 34.78% to above 65%. This variation reflects uneven planting patterns, where certain plots were dominated by open grass and hardscape, while others were located beneath dense tree canopies. Although some plots recorded canopy values exceeding 100% due to overlapping crowns and image processing limitations, these values were interpreted comparatively to indicate very dense canopy conditions rather than absolute measurements. Overall, the findings demonstrate that canopy distribution within a single apartment complex is far from uniform and creates distinct microclimatic conditions at the human scale.

3.1 Termal Comparative Thermal Performance of Semi-Public Spaces

The results reveal clear differences in thermal performance associated with variations in vegetation canopy and landscape configuration. A comparison of average canopy coverage and Physiological Equivalent Temperature (PET) across three semi-public spaces at Transpark Cibubur Apartment can be seen in Fig. 3. The Swimming Pool Area exhibits the best thermal condition, with the highest average canopy coverage (75.08%) and the lowest PET value (31.2 °C). This indicates that dense tree canopy, combined with the presence of water elements, effectively reduces microclimatic heat stress. In contrast, the West Communal Garden shows the lowest canopy coverage (57.15%) and the highest PET value (36.4 °C), reflecting substantial thermal stress due to limited shading and extensive hardscape surfaces.

The East Communal Garden demonstrates intermediate performance, with an average canopy coverage of 60.20% and a PET value of 34.8 °C. Although thermally better than the West Communal Garden, conditions in this area remain above the comfort threshold for humid tropical climates. Overall, the comparison confirms an inverse relationship between canopy coverage and PET at the micro scale, highlighting vegetation canopy as a key factor in improving outdoor thermal comfort in semi-public spaces of middle-income vertical housing.

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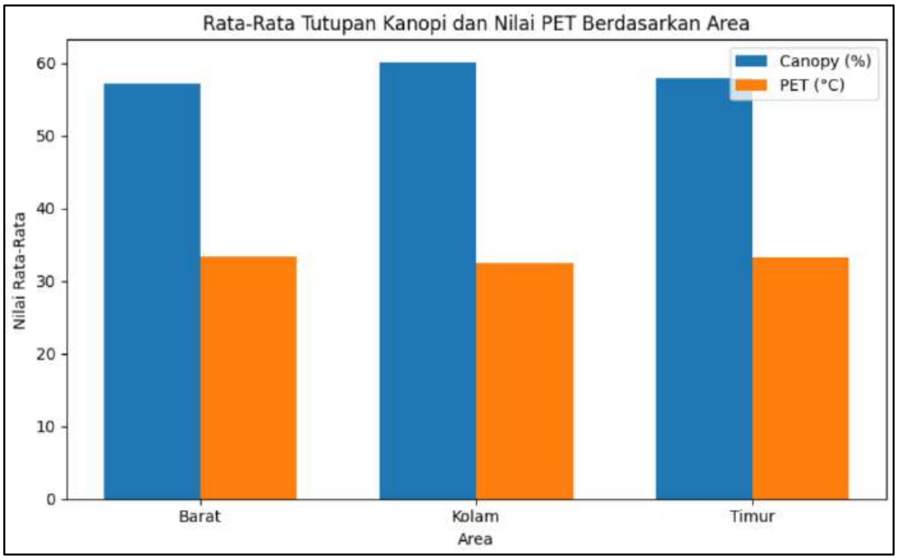

Figure 3 Canopy Coverage by Area
(Source: Author's Analysis, 2025)

3.2 Relationship Between Canopy Coverage and PET

Regression analysis reveals a strong negative relationship between canopy coverage and PET across the 12 measurement plots. As canopy coverage increased from 34.78% to 71.66%, PET values decreased from 38.2 °C to 30.1 °C. The linear regression model yielded the following equation:

$$\boldsymbol{PET} = \mathbf{52.84} - \mathbf{0.289} \times (\%\, \boldsymbol{canopy\ coverage})$$
$$\text{with } \boldsymbol{R}^2 = \mathbf{0.892} \text{ and } \boldsymbol{p} < \mathbf{0.001}.$$

This result indicates that approximately 89% of the variation in PET can be explained by differences in canopy coverage alone. Practically, an increase of 10% in canopy coverage corresponds to an average PET reduction of approximately 2.9 °C at the microclimatic scale. Such a reduction is physiologically meaningful in humid tropical environments, where small temperature decreases can substantially improve outdoor comfort. These findings reinforce the role of tree canopy as a primary determinant of thermal comfort in semi-public outdoor spaces of vertical housing, even without extensive land availability.

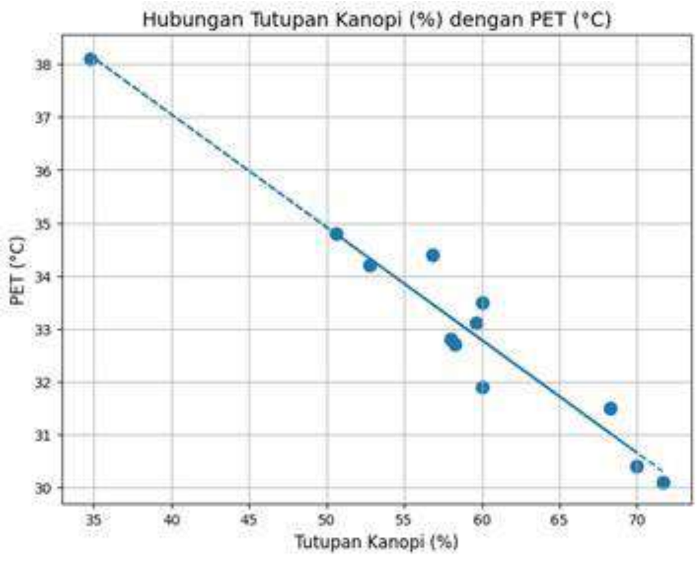

Figure 4 Relationship Between Canopy Coverage and PET
(Source: Author's Analysis, 2025)

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3.3 Micro-scale Thermal Hotspot and Cool Spots

The spatial distribution of PET values reveals the presence of distinct micro-scale thermal hotspots and cool spots within the apartment complex. Plots with canopy coverage exceeding 70% consistently functioned as cool spots, with PET values close to or below 32 °C. These areas were typically located beneath dense tree canopies and, in some cases, adjacent to water elements.

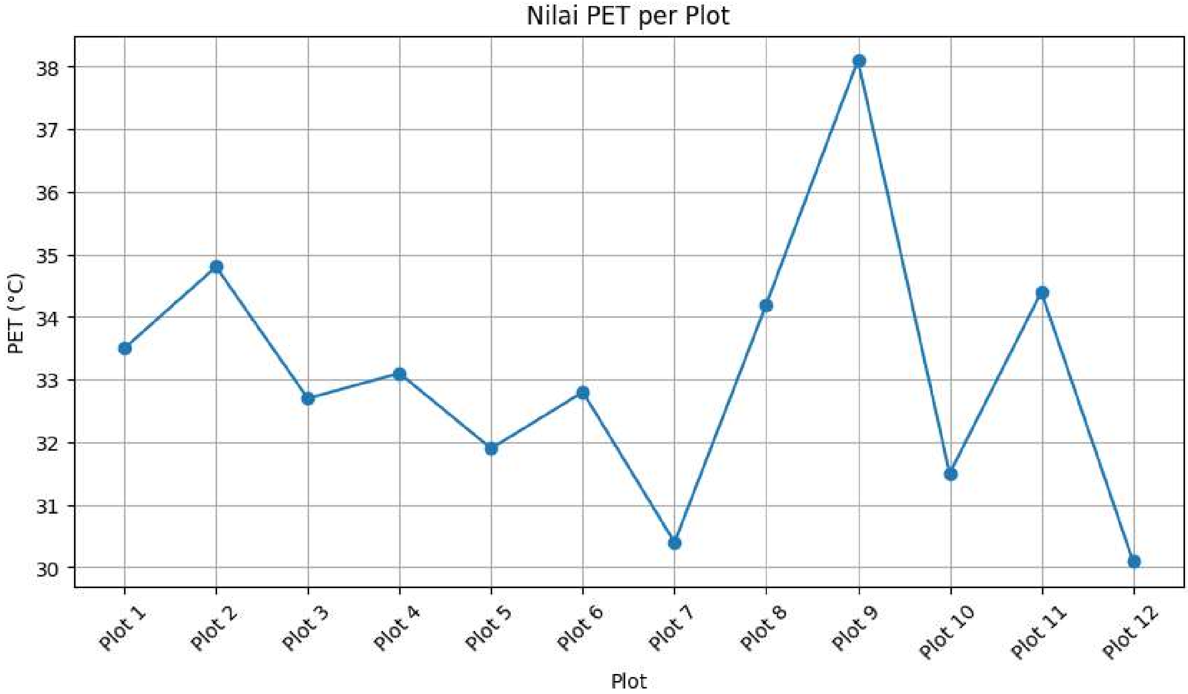

Figure 5 Variation of Canopy Coverage by Plot
(Source: Author's Analysis, 2025)

Conversely, plots with canopy coverage below 50% formed localized thermal hotspots, particularly where hardscape surfaces dominated and solar exposure was unobstructed. The maximum PET difference between plots reached 8.1 °C, despite their close proximity, highlighting the importance of localized landscape configuration rather than broader urban context alone. This pattern demonstrates that thermal comfort in vertical housing environments is highly sensitive to micro-scale design decisions, especially the spatial arrangement and density of vegetation canopy.

3.4 Integration of Objective Measurements and User Perceptions

A survey of 58 residents indicates that perceived thermal comfort is consistent with the objective measurement results. The majority of respondents rated the communal gardens as "insufficiently shaded" (mean score 2.69) and "thermally uncomfortable" during daytime hours (2.74), whereas the swimming pool area was perceived as "significantly cooler" (4.43). Approximately 95% of respondents expressed strong support for the addition of large-canopy trees, underscoring the perceived need to enhance vegetation coverage. Triangulation with PET measurements reveals that areas with the highest thermal stress, namely the communal gardens, are the least frequently used, while areas with the lowest PET values, particularly the swimming pool area, are perceived as the most comfortable and are used more intensively. These findings confirm that thermal comfort is a key determinant of micro-scale green space utilization in vertical housing environments.

Semi-structured interviews with apartment management further reinforce these findings. The management acknowledged that complaints regarding excessive heat in

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communal gardens are recurrent and identified limited planting space and the predominance of narrow-canopy tree species (such as palms and ketapang) as primary constraints to increasing canopy coverage. The swimming pool area is informally used as an internal benchmark due to its consistently cooler thermal conditions, which result from the combined effects of vegetation shading and water elements. Management expressed support for the addition of large trees, provided that non-invasive root systems are selected and maintenance costs remain manageable. These insights demonstrate that increasing canopy coverage is not only scientifically justified but also socially and institutionally supported.

Table 4 Residents' Perceptions and Management Perspectives on Thermal Comfort

Aspect	Resident Survey Findings (n = 58)	Management Interview Findings	Implications for the Study
Perception of vegetation in communal gardens	Vegetation is perceived as "insufficiently shaded" (Mean = 2.69).	Acknowledges the dominance of narrow-canopy tree species (e.g., palms and ketapang).	Indicates the need to increase canopy coverage in communal gardens.
Perception of thermal comfort	Communal gardens are perceived as "thermally uncomfortable" during daytime hours (Mean = 2.74).	Heat-related complaints from residents are a recurring issue.	Consistent with high PET values recorded in these areas.
Comparison between swimming pool area and communal gardens	The swimming pool area is perceived as "significantly cooler" (Mean = 4.43).	The swimming pool area is used as an internal benchmark for thermal comfort.	The combination of vegetation shading and water elements yields the best thermal performance.
Frequency of space use	Communal gardens are infrequently used due to excessive heat.	More shaded areas are consistently more actively used.	Confirms thermal comfort as a key determinant of space utilization.
Resident support for additional trees	95% of respondents agree or strongly agree with adding large-canopy trees.	Strong institutional support, provided non-invasive root systems are used.	Indicates strong social and institutional support for implementation.
Constraints to increasing canopy coverage	–	Limited planting space, structural risks, and high maintenance costs.	Highlights the importance of selecting appropriate tree species with non-invasive roots.

(Source: Author's Analysis, 2025)

3.5 Implications for Design and Sustainable Development

The findings confirm that optimizing canopy coverage in micro-scale urban green spaces is an effective nature-based strategy for mitigating urban heat stress in middle-income vertical housing. Targeting canopy coverage levels of approximately 70–75% enables semi-public spaces to function as thermal refuges, even under peak daytime heat conditions. From a sustainability perspective, these results support SDG 11 (Sustainable Cities and Communities) by improving the quality and usability of semi-public green spaces, and SDG 13

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(Climate Action) through climate adaptation strategies at the micro-urban scale. By focusing on vegetation-based solutions that are spatially efficient and cost-effective, this approach is particularly relevant for dense tropical cities facing land constraints.

4. CONCLUSION

This study demonstrates that vegetation canopy coverage plays a decisive role in mitigating Urban Heat Island (UHI) effects at the micro-scale of vertical residential environments in Jakarta. Empirical evidence from Transpark Apartment, Cibubur, reveals a strong inverse relationship between canopy density and Physiological Equivalent Temperature (PET), with a coefficient of determination exceeding 0.85. The results indicate that canopy coverage of approximately 75% is sufficient to reduce PET values to 31.2°C, corresponding to the upper threshold of outdoor thermal comfort in humid tropical climates, whereas areas with canopy coverage below 58% experience PET values above 36°C, indicative of severe heat stress. The consistency between objectively calculated PET values and residents' subjective thermal perception, as reflected in the Thermal Sensation Vote (TSV), confirms the reliability of PET as an indicator of outdoor thermal comfort in semi-public residential spaces. Importantly, the findings highlight that micro-scale urban green spaces (Micro-UGS) embedded within residential boundaries provide significantly greater immediate physiological cooling—approximately 4.8 times more effective—than city-scale greening interventions. This study contributes to the growing body of microclimate research by establishing a quantitative canopy coverage threshold for thermally functional semi-public spaces in vertical housing, offering evidence-based design guidance for architects, developers, and urban policymakers seeking to enhance climate resilience in dense tropical cities.

Based on the synthesis of quantitative microclimatic data and residents' social survey responses, this study formulates several design-oriented recommendations for future vertical housing developments in tropical urban contexts. The findings indicate that a minimum vegetation canopy coverage of approximately 70–75% should be targeted for semi-public and communal outdoor spaces in order to effectively transform these areas into functional thermal refuges during peak heat periods. To achieve this threshold, vegetation strategies should prioritize broad-leafed shade trees with a high Leaf Area Index (LAI), rather than predominantly ornamental planting, with trees strategically clustered to ensure continuous shading along pedestrian circulation routes and activity zones. Beyond design considerations, the results suggest that outdoor thermal comfort criteria particularly PET-based performance targets should be formally integrated into building management guidelines and green building certification systems for high-rise residential developments in Indonesia. Improving the microclimatic performance of communal spaces not only enhances thermal comfort but also reinforces their social function as active shared environments, thereby contributing to the achievement of Sustainable Development Goal 11 and improving overall urban quality of life. In this context, the strategic management of tree canopy density should be understood not as an aesthetic preference, but as a critical climate-adaptation strategy for sustaining livable vertical housing in tropical megacities.

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