FiadMed

Built Environment Innovations (BEI)
Vol. 1, No. 2, pp. 68-83

Research Article

Green Open Space and Its Role in Regulating Thermal Comfort Based on THI Analysis in a Tropical Campus Environment

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Abstract

Green open space (GOS) plays an important role in regulating the microclimate and enhancing thermal comfort in tropical campus environments. This study examined the distribution of vegetation and its impact on thermal comfort at Syiah Kuala University, Banda Aceh, Indonesia. Vegetation cover was analyzed using the Normalized Difference Vegetation Index (NDVI), while field measurements of air temperature, relative humidity, and wind speed were conducted at ten observation points across three zones of the Faculty of Engineering campus. The results showed that low or very sparse vegetation occupied 61.87% of the area, while pavement and built surfaces accounted for 22.43%. Moderate vegetation covered 9.06% of the campus, and high-density tree canopies comprised only 3.63%. Thermal comfort analysis based on the Temperature Humidity Index (THI) revealed notable variation across zones. Zone B, characterized by extensive shading from vegetation, recorded the lowest average temperatures and the most comfortable THI values, while Zones A and C, dominated by built-up surfaces with minimal vegetation, experienced the highest thermal stress. These findings confirmed that vegetation density and distribution strongly influenced thermal comfort by lowering air temperature, maintaining humidity, and moderating airflow. The study underscored the critical importance of green open space planning in mitigating heat stress on tropical university campuses and provided practical recommendations for sustainable campus development.

Keywords: Green Open Space; Microclimate; Thermal Comfort; Urban Heat Island; Vegetation.

Introduction

Rapid urbanization in tropical cities has led to an increase in building construction and a decrease in green open space (GOS) in urban areas [1,2]. This phenomenon has contributed to the accumulation of surface heat or Urban Heat Island (UHI), which negatively affects the thermal comfort of urban residents and overall environmental quality [3]. The decline in vegetation in urban environments allows hard surfaces to dominate the land, thereby increasing

Article History
Received: 1 Oct, 2025; Revised: 22 Nov, 2025;
Accepted: 8 Dec, 2025; Published: 12 Dec 2025

heat absorption and transmission. Therefore, GOS management serves as an essential strategy to balance urban ecosystems and create a comfortable microclimate [4,5].

Green open spaces have an important role in heat mitigation and microclimate regulation in urban areas, including on university campuses [6,7]. Vegetation helps lower surface temperature through evapotranspiration and provides a local cooling effect for pedestrians and users of campus facilities [8,9]. In addition, the presence of GOS supports social activities, recreation, and the psychological well-being of students and academic staff [10]. High-quality GOS is an indicator of a healthy and comfortable campus environment for learning and activities [11,12].

Previous research showed that vegetation distribution and surface composition significantly affect thermal comfort levels [13,14]. Zones with high vegetation tend to have lower temperatures and more stable humidity than non-vegetation areas [15]. Conversely, areas dominated by concrete and asphalt often experience temperature increases of up to 4–6 °C compared to forested areas [1]. This confirms that GOS regulation is not merely aesthetic, but also essential for thermal comfort and environmental health [16].

In the campus environment, thermal comfort is essential to support students' academic productivity and social interaction [17]. Thermal discomfort due to overheating can reduce concentration, increase fatigue, and potentially pose health risks such as heat stress [18]. Therefore, design strategies that integrate vegetation, building layout, and hard surfaces become crucial. Research on the effect of GOS on thermal comfort on campus remains limited, especially in medium-sized cities such as Banda Aceh [7,19].

The city of Banda Aceh experienced significant urban development, including in the campus area of Universitas Syiah Kuala (USK). The Faculty of Engineering is one of the locations that underwent the conversion of green land into buildings and supporting facilities, resulting in uneven GOS distribution. This condition highlights the need to evaluate microclimatic conditions and thermal comfort on campus. Thus, this study aims to address the knowledge gap regarding the impact of land conversion on thermal comfort in tropical campuses.

One of the thermal comfort indicators used is the Temperature Humidity Index (THI), which combines air temperature and relative humidity to assess thermal conditions [13,20]. THI provides quantitative information regarding areas that are comfortable and uncomfortable for users. Previous research showed that areas with adequate vegetation have lower THI, while non-vegetation areas have high THI and thermal discomfort [10]. Thus, THI is an important tool for evaluating the microclimate conditions of the campus.

Field measurements of air temperature, humidity, and wind speed were carried out at strategic points representing variations in vegetation and built-up space [21]. These measurements offer insights into the interaction between vegetation, hard surfaces, and architectural elements in influencing thermal comfort. The measurement results were then analyzed spatially to map the distribution of temperature and airflow [22,23], enabling a more accurate and representative evaluation of microclimate conditions.

Vegetation availability on the USK campus remains limited, with much of the area consisting of hard surfaces, accompanied by moderate vegetation and smaller pockets of tall vegetation. These conditions lead to heat accumulation during the day, while existing vegetation provides only limited cooling. This uneven distribution results in variations in thermal comfort across campus zones and serves as the basis for designing more effective GOS interventions.

Tall vegetation, such as shady trees in campus parks, was shown to reduce surface temperatures by up to 5°C and enhance thermal comfort for pedestrians [6]. Moderate vegetation, although larger in area, only provides a moderate effect on temperature and humidity [24,25]. Therefore, planning for adding vegetation, including the integration of a green roof or vertical greenery system, is an appropriate strategy to enhance thermal comfort in dense building areas [26].

In addition to vegetation, architectural elements and building layouts affect wind circulation and heat distribution [27,28]. Semi-open zones with a combination of vegetation and buildings can support better airflow, thereby lowering localized microclimatic temperatures at several points [29]. However, areas with predominance of buildings and hard surfaces show varying wind speeds and high heat accumulation. This shows the importance of holistic design that considers the interaction between vegetation and architectural elements [30,31].

Thermal comfort depends not only on the presence of vegetation, but also on its distribution, density, and the characteristics of surface materials [32]. Areas exposed to direct sunlight without vegetation cover tend to have high THI and thermal discomfort. On the other hand, zones with shady trees or dense vegetation have low THI and more comfortable conditions [33]. This understanding is important for designing evidence-based interventions in tropical campus environments.

This study combines quantitative approaches, spatial analysis, and thermal evaluation to provide a holistic picture of thermal comfort on campus. This interdisciplinary approach allows for a thorough evaluation of the impact of GOS on temperature, humidity, and airflow. The results of the study are expected to provide recommendations for the design and management of GOS that apply to other universities in Indonesia and other tropical countries.

In addition to the technical aspect, the existence of GOS also contributes to the psychological well-being and quality of social interaction of campus users [10]. Parks, green paths, and shady areas become recreational spaces that support students' mental health. Thus, GOS management is not only about heat mitigation, but also about improving the quality of life and productivity in the campus environment [34-36].

Overall, the study highlights the importance of integrating GOS into tropical campus planning to reduce UHI effects and improve thermal comfort. This study also provides a new contribution to the literature on the influence of GOS on thermal comfort in medium-sized urban campuses, particularly in Banda Aceh. With a clearer understanding of vegetation distribution and its interaction with physical elements, GOS planning strategies can be further optimized.

This research aims to address the knowledge gap related to thermal comfort in tropical campuses and offer a scientific basis for more effective GOS management. The Faculty of Engineering at Universitas Syiah Kuala is used as a representative case of an area with low-to-moderate vegetation density and a high proportion of built-up spaces. The findings of this study are expected to inform design, planning, and policy interventions that enhance thermal comfort, environmental performance, and user well-being on campus.

Recent studies indicate that empirical evidence integrating NDVI-based vegetation analysis with THI-derived thermal comfort assessment at the campus scale remains limited, particularly in medium-sized tropical cities such as Banda Aceh. This study responds to that gap by combining satellite-derived vegetation indicators with field-based microclimate measurements to examine how spatial variations in vegetation influence outdoor thermal comfort in the Faculty of Engineering area. Through this integrative approach, the research provides a more comprehensive understanding of the microclimatic effects of vegetation structure and offers evidence-based insights to support sustainable campus planning and climate-responsive design strategies in humid tropical environments.

Materials and Methods

This research was carried out at the Syiah Kuala University (USK) Campus, which is located in Banda Aceh City, Aceh Province, Indonesia. Geographically, this campus is located in the Darussalam area, Syiah Kuala District, at the coordinates 5°34′57" North Latitude and 95°22′37" East Longitude. The Darussalam area is known as the largest higher education center in Aceh, with direct access to the east coast of Banda Aceh City. The USK campus environment is characterized by diverse land uses, including academic areas, supporting facilities, and green open spaces. These geographical conditions in the humid tropics made the campus an ideal location for research related to thermal comfort, especially in outdoor spaces influenced by the interaction of vegetation, buildings, and microclimate (**Figure 1**).

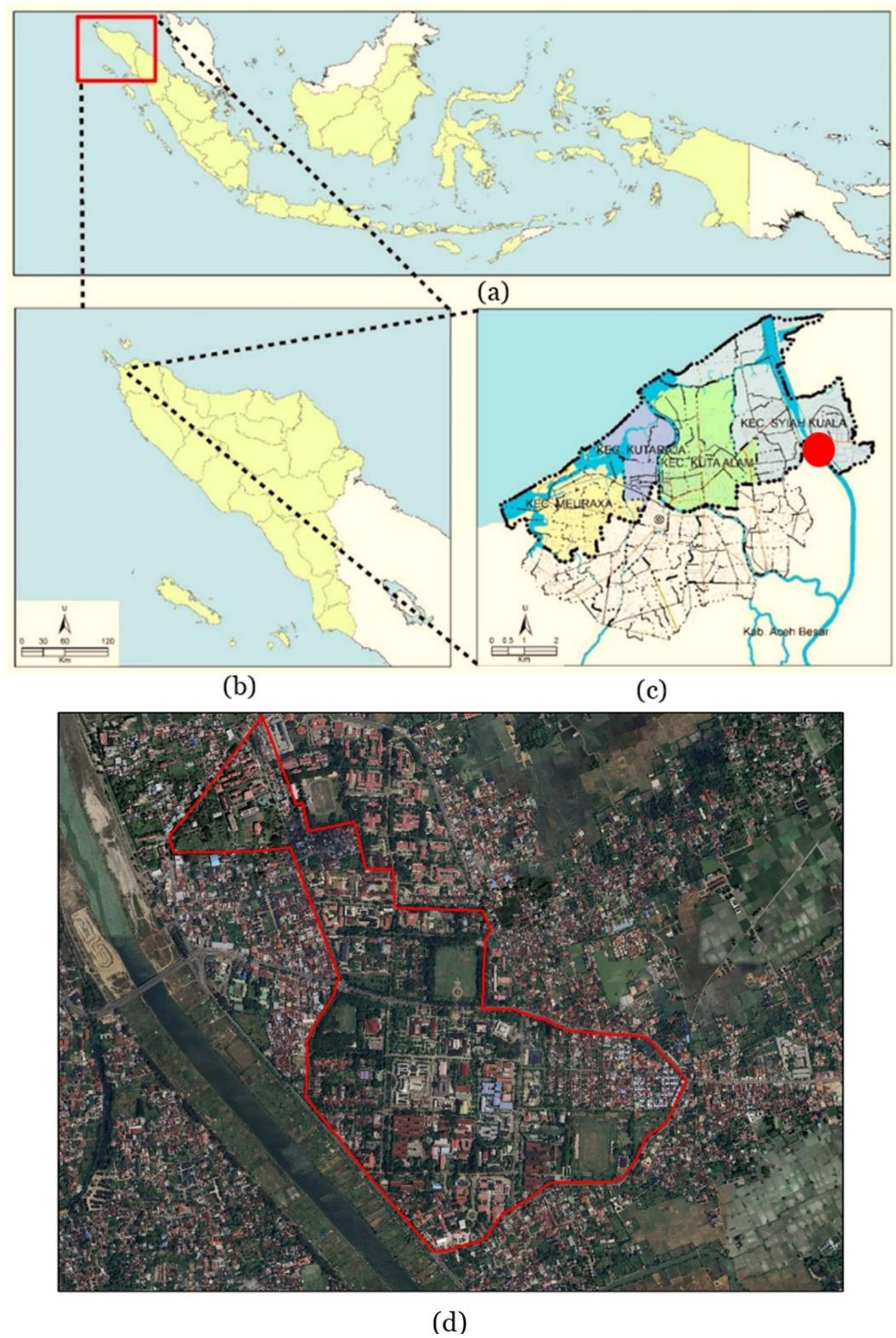

Figure 1. Map of the Research Location (a) Map of Indonesia; (b) Aceh Province; (c) Banda Aceh City; (d) Syiah Kuala University Campus, Kopelma Darussalam

The Faculty of Engineering was selected as the primary study area because it presented a representative spectrum of spatial conditions—ranging from shaded green spaces to highly exposed built environments—necessary for evaluating microclimatic variation in a tropical campus setting. For analytical clarity, the area was divided into three zones based on dominant land-cover characteristics and the degree of shading. Zone A comprised open spaces with heterogeneous microclimates, ranging from shaded parking areas to fully exposed fields and pedestrian routes, which allowed the examination of thermal differences driven by shading contrasts. Zone B functioned as a transitional environment where vegetation and structural elements were more evenly distributed, creating intermediate conditions that varied from shaded pedestrian paths to moderately shaded garden spaces. Zone C represented the most built-up portion of the study area, dominated by hard surfaces such as parking areas and building complexes, while still containing localized shaded pockets near structures.

Ten measurement points (A-FT1 to C-FT10) were strategically placed to capture the diversity of microenvironments, with each point representing a distinct combination of surface material, vegetation presence, shading intensity, and building orientation (**Figure 2**). This zoning framework enabled a systematic comparison of thermal comfort outcomes—ranging from comfortable shaded locations to thermally stressed exposed areas—and provided a coherent basis for interpreting the Temperature Humidity Index (THI) results.

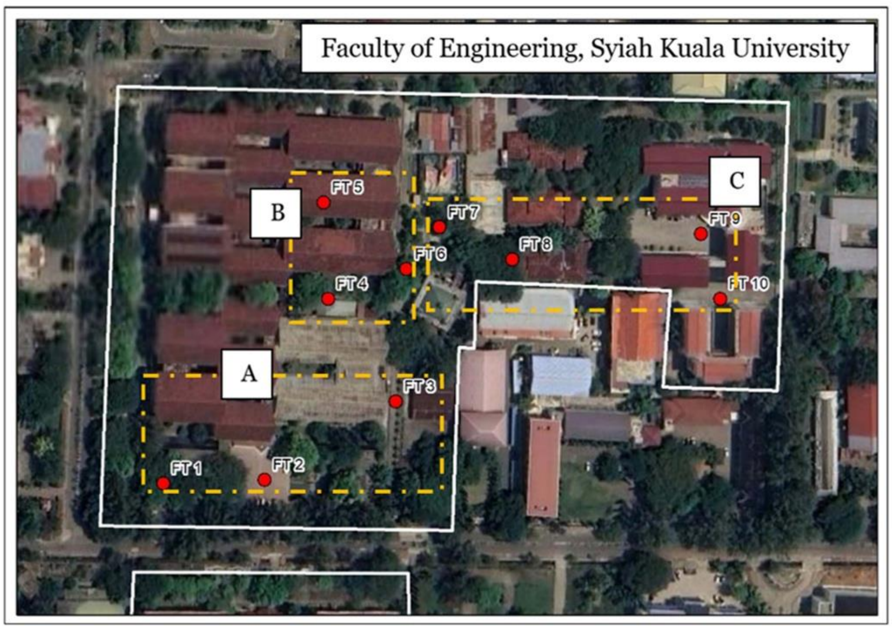

Figure 2. Data Collection Location Points

Data collection was carried out through field measurements of microclimate parameters, which included air temperature, relative humidity, and wind speed. Temperature and humidity were measured using a digital thermo-hygrometer with an accuracy of ±0.1 °C and ±2% RH, while wind speed was recorded using a portable anemometer with an accuracy of ±0.1 m/s. Each point was measured repeatedly over three time periods: morning (08:00–11:00), afternoon (12:00–14:00), and late afternoon (15:00–17:00), to capture daily microclimatic fluctuations. The data obtained were averaged for each point. To ensure temporal representativeness, microclimate measurements were conducted over three consecutive days (27–29 September 2024). Repeating measurements across multiple days helped reduce short-term weather effects and strengthened the reliability of the dataset.

In addition to the microclimate parameters, vegetation conditions and surface types at each point were also documented. Vegetation was classified into three categories, namely low, moderate, and high, based on vegetation density, height, and canopy coverage, including the area of the canopy that covers the ground surface. Surface types (hardscape) were identified as concrete, asphalt, paving blocks, or other open surfaces that have no vegetation. This approach allowed the analysis of the correlation between vegetation distribution and surface type with the level of thermal comfort in each zone.

Thermal comfort analysis was performed by calculating the Temperature Humidity Index (THI) for each observation point. THI was calculated based on a standard formula that combines air temperature and relative humidity [16]. THI was used to indicate the level of thermal comfort in an area that is affected by temperature (T) and relative humidity (RH) factors. The THI value was further categorized into three comfort levels: comfortable, uncomfortable, and very uncomfortable (**Table 1**). These results were used to assess the effectiveness of vegetation and surfaces in reducing heat stress in open space users. The formula used to determine THI is as follows:

$$THI = 0.8T + \frac{RHxT}{500} \tag{1}$$

Notes:
THI: Temperature Humidity Index
T: Temperatures (^{o}C)
RH: Relative humidity (%)

Table 1. THI Values and Comfort Criteria in Tropical Climates

THI Value	Comfort Criteria
< 29	Comfortable
29 – 30.5	Uncomfortable
>30.5	Very uncomfortable

The thermal comfort thresholds applied in this study (< 29; 29–30.5; > 30.5 °C) follow the classification proposed by Frick and Suskiyatno [16], ensuring consistency in the interpretation of THI values across all observation points. To support the thermal comfort assessment, vegetation analysis was conducted using NDVI derived from Landsat 8 OLI/TIRS imagery acquired on 24 September 2024 with a spatial resolution of 30 meters. NDVI values were calculated using the formula NDVI = (NIR – Red) / (NIR + Red), and the resulting indices were classified into five land-cover categories: water or other highly reflective surfaces (NDVI < 0.00), non-vegetation or built-up areas (0.00–0.20), low or very sparse vegetation (0.20–0.30), moderate vegetation (0.30–0.40), and high or dense vegetation (NDVI > 0.40). Integrating this spatial vegetation assessment with field-based microclimate measurements enhanced methodological transparency and strengthened the reproducibility of the study.

Data processing was conducted using Microsoft Excel to analyze the distribution, average, and variation of microclimate parameters between zones. Data on temperature, humidity, and wind speed were analyzed descriptively to evaluate the difference in thermal conditions in the dominant zone of vegetation compared to the dominant zone of buildings. Furthermore, the relationship between vegetation level, surface type, and thermal comfort was analyzed using distribution graphs and comparison tables between zones.

The selection of THI as the main method in this study is based on several considerations. First, THI is a simple index that is relevant for humid tropical climates, as it combines temperature and humidity, which are the dominant factors determining comfort in the region.

Second, compared to more complex indices such as the Predicted Mean Vote (PMV), Physiological Equivalent Temperature (PET), or Universal Thermal Climate Index (UTCI), THI is more practical to apply in the field because it does not require additional parameters such as direct solar radiation, metabolic rate, or clothing insulation, which are difficult to obtain consistently in outdoor measurements. Third, the use of THI allows comparisons with similar studies in tropical regions that have used this index extensively, making the results easier to contextualize. Thus, THI was seen as the most appropriate approach to answer the objectives of this research.

However, this method has limitations. THI does not consider factors of direct solar radiation, wind speed in detail, nor subjective aspects of human comfort such as activity level and clothing insulation. This can cause the results of the analysis to be less representative of real comfort conditions in the field. Therefore, the results of this study need to be understood as a preliminary picture based on simple indicators. For further research, a combination with other indices such as PET or UTCI is recommended to make the evaluation of thermal comfort in tropical campus environments more comprehensive.

All research methods were described in detail so that they can be replicated by other researchers. The measurement procedure was carried out by paying attention to the consistency of weather conditions, strategic point selection, and the use of calibrated instruments to ensure the accuracy and validity of the data. With this approach, the research was expected to produce objective and systematic information about thermal comfort in the outdoor space of the Faculty of Engineering, Syiah Kuala University.

Results

The land-cover assessment of the USK campus indicates that the total area of approximately 129.79 hectares is dominated by low or very sparse vegetation surfaces covering 80.30 hectares. This category, consisting primarily of grass fields and scattered shrubs, constitutes the largest landscape component, followed by pavement and built structures, which occupy 29.11 hectares. Moderate vegetation—composed of moderately dense tree stands—covers 11.76 hectares, while high-density canopy vegetation extends across only 4.71 hectares. The remaining 3.91 hectares fall into other non-vegetation categories. This spatial composition forms the baseline for examining the distribution and functional contribution of green and built elements in shaping outdoor thermal conditions across the campus (**Figure 3**).

Visual interpretation of the NDVI map corroborates the proportional dominance of low or very sparse vegetation surfaces, which account for 61.87% of the total land area. These open vegetated grounds, despite their ecological value, provide only limited shading and therefore exhibit weaker cooling capacity than areas with moderate or high-density tree cover. Pavement and built areas, representing 22.43% of the campus, appear clearly as zones with low NDVI signatures and are associated with high surface heat absorption. In contrast, moderate and high-density vegetation zones, which together constitute only 12.69% of the campus, form relatively small but critical cooling pockets that create more favorable microclimatic conditions. The spatial clustering of these vegetated zones highlights their insufficient distribution relative to the extensive low or very sparse vegetation and built surfaces.

The thermal implications of this land-cover composition are evident in the contrasting comfort conditions across campus spaces. While low or very sparse vegetation areas dominate the landscape, their limited shading capacity makes them less effective in mitigating ambient temperature rises, particularly during peak daytime hours. Built and paved zones, comprising 22.43% of the area, amplify thermal stress through heat storage and re-radiation, negatively influencing outdoor comfort. Conversely, areas with moderate and high-density vegetation—although occupying only 9.06% and 3.63% of the campus, respectively—demonstrate stronger microclimatic moderation through shading and evapotranspiration. These proportional patterns align with field measurements showing lower temperatures and THI values in densely vegetated zones, reinforcing the crucial role of strategically distributed greenery in improving thermal comfort across the campus landscape.

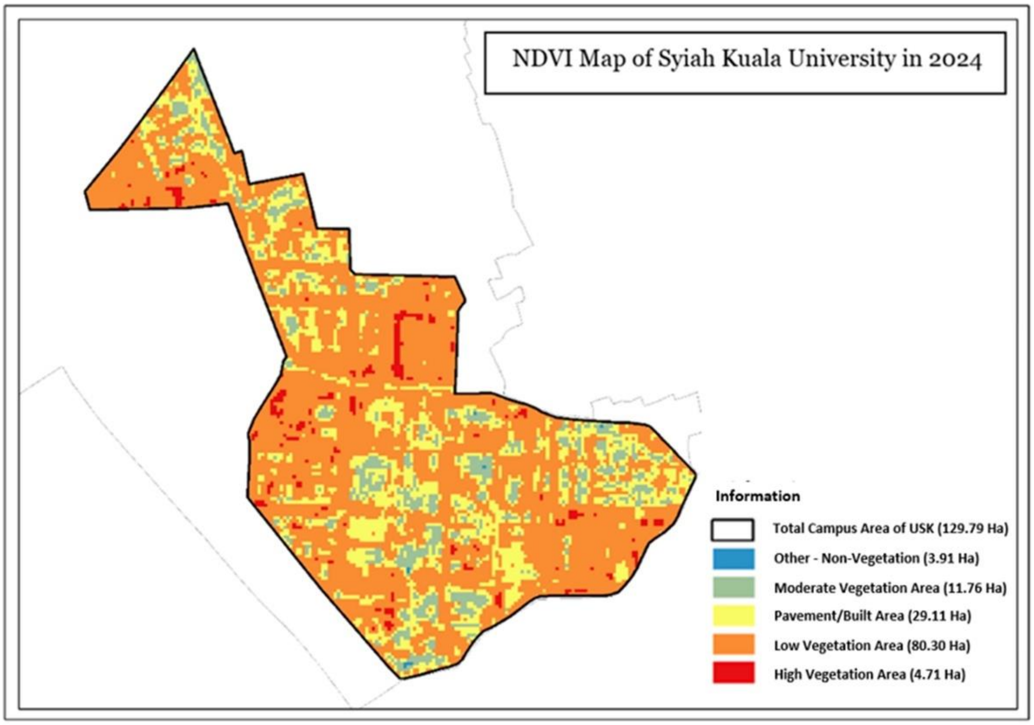

Figure 3. NDVI Map of Syiah Kuala University in 2024

The uneven vegetation cover identified through the NDVI analysis was associated with clear differences in microclimatic conditions across the campus. Areas dominated by hard surfaces were more prone to heat accumulation throughout the day, while locations with dense vegetation experienced notable cooling effects generated by shading and evapotranspiration. As such, the NDVI map not only offered a spatial overview of vegetation patterns but also served as a reliable indicator of potential thermal hotspots, which aligned with the temperature fluctuations observed during field measurements.

To deepen the analysis, temperature measurements were conducted in the Faculty of Engineering area, which functioned as a microcosm of the broader campus due to its mixture of building clusters, semi-open zones, and green spaces. This setting allowed a more detailed evaluation of how different land-cover characteristics influenced diurnal temperature profiles and provided an empirical basis to validate NDVI-derived interpretations. Within this framework, Zone A consistently demonstrated lower temperatures, particularly at point A-FT1, which recorded the lowest average value of 27.4 °C. These cooler conditions were attributed to the presence of mature trees and continuous canopy cover, which reduced direct solar exposure and slowed heat accumulation throughout the day.

In contrast, Zone B showed greater temperature variation due to its semi-open character and uneven vegetation distribution. Point B-FT4 remained relatively cool because of substantial shading, while B-FT5 reached 28.7 °C, which was classified as comfortable but was close to the upper comfort threshold, as a result of adjacent hard surfaces and limited vegetation. Zone C exhibited the highest average temperatures among all zones, with points C-FT9 and C-FT10 recording 29.0–29.1 °C, reflecting their exposure to direct sunlight and extensive built-up surfaces. These findings were consistent with the diurnal patterns shown in the temperature diagram, confirming that variations in temperature peaks and cooling rates were strongly driven by differences in vegetation density, shading availability, and surface materials (**Figure 4**).

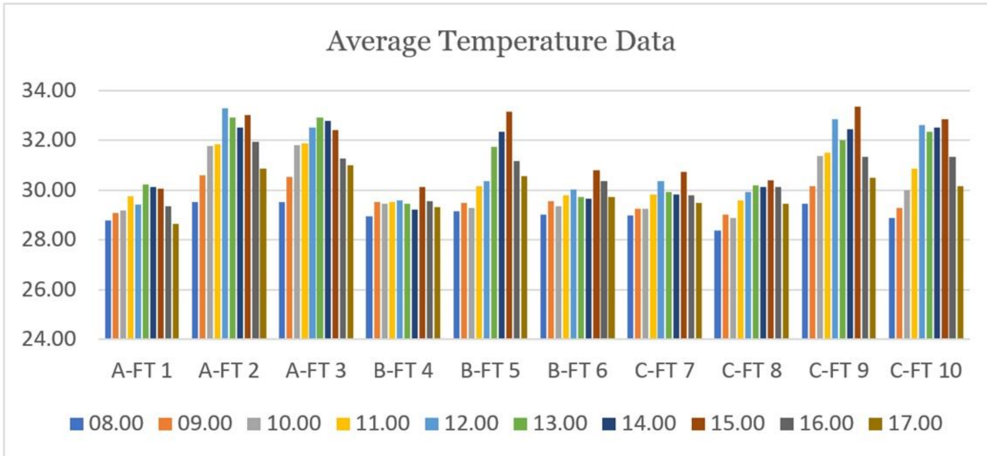

Figure 4. Average Temperature Data

The Average Temperature Data diagram illustrates the variation in air temperature across ten measurement points (A-FT1 to C-FT10) from 08:00 to 17:00. Overall, temperatures increase steadily from morning to midday and decline again in the late afternoon, with peak values occurring between 13:00 and 15:00 at nearly all locations. Points such as A-FT1 and B-FT4 consistently exhibit the lowest temperatures throughout the day due to substantial vegetation cover that provides shade and reduces heat absorption. In contrast, points A-FT2, A-FT3, B-FT5, C-FT9, and C-FT10 show the highest temperature increases—particularly between 12:00 and 15:00—reflecting their exposure to direct sunlight and dominance of hardscape surfaces. This pattern highlights the strong influence of land-cover characteristics on diurnal temperature fluctuations, where areas shaded by trees maintain more stable and lower temperatures compared to locations lacking vegetation.

The analysis of relative humidity showed patterns that aligned closely with the spatial distribution of vegetation across the study area. In Zone A, point A-FT2 recorded the highest humidity level at 78%, a condition that was supported by substantial evapotranspiration from tall and dense vegetation. By contrast, point A-FT1—although located within the same zone—showed a noticeably lower humidity value of 70% because it was more exposed to direct sunlight and lacked continuous shading. These differences demonstrated how even small variations in canopy density influenced the ability of an area to retain moisture throughout the day.

In Zone B, relative humidity values remained moderate, ranging from 57–70%. Point B-FT6 exhibited the highest humidity within this zone due to its surrounding vegetation, while point B-FT5 consistently recorded lower values because it was situated in an open area dominated by hard surfaces. These patterns indicated that the interaction between vegetation and exposed surface materials shaped the micro-scale moisture dynamics in semi-open environments. Meanwhile, Zone C consistently recorded the lowest relative humidity values, ranging from 57–67%. Point C-FT8, which was enclosed by built structures, maintained stable but reduced humidity levels throughout the measurement period, reflecting the minimal contribution of evapotranspiration in built-up spaces. This overall trend reinforced the importance of increasing vegetation cover in highly developed areas to improve their microclimatic moisture conditions (**Figure 5**).

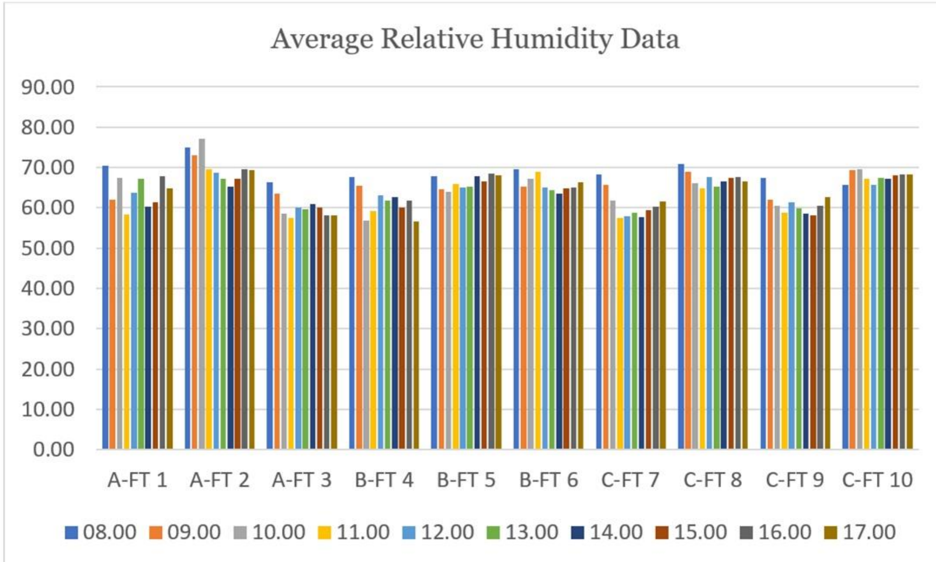

Figure 5. Average Relative Humidity Data

The Average Relative Humidity Data diagram shows the variation in relative humidity at the ten measurement points from 08:00 to 17:00, revealing a consistent pattern in which shaded or vegetated areas maintain higher humidity than open, exposed locations. Points A-FT2 exhibit the highest humidity levels, reaching approximately 70–78% in the morning before gradually decreasing as midday temperatures rise. Conversely, exposed points such as A-FT3, B-FT4, and C-FT7 record the lowest humidity values, ranging from 57–67%, indicating limited evapotranspiration contributions from vegetation. Hourly variations at each point show a general trend of declining humidity toward midday, followed by a slight increase in the late afternoon. Overall, the diagram demonstrates that vegetation density and solar exposure are key determinants of an area's ability to retain atmospheric moisture in the tropical campus environment.

Wind speed patterns varied noticeably across the three zones and were strongly shaped by land-cover characteristics and vegetation structure. In Zone A, wind speeds were generally low to moderate, with several points experiencing reduced airflow where dense vegetation acted as a physical barrier. For example, A-FT2 recorded consistently low wind speeds because tree canopies and nearby structural elements restricted air movement, while A-FT1 and A-FT3 experienced comparatively stronger airflow due to their more open spatial conditions.

In Zone B, wind speeds ranged widely and reflected the mixed configuration of semi-open spaces. Point B-FT5 registered some of the lowest values because surrounding vegetation and nearby buildings obstructed airflow, whereas B-FT4 showed smoother and higher wind velocities consistent with its more open pedestrian corridor. These differences indicated that vegetation placement and building orientation jointly influenced wind behavior within transitional spaces.

Zone C displayed the most pronounced variation, with wind speeds spanning from very low to the highest recorded values among all measurement points. C-FT7, surrounded by built structures, maintained low and stable airflow throughout the day, while more exposed locations such as C-FT8, C-FT9, and C-FT10 recorded substantially higher wind speeds that occasionally exceeded 1.0 m/s. This pattern demonstrated that hardscape-dominated areas with minimal obstruction facilitated stronger air circulation, whereas clustered buildings reduced wind penetration and contributed to micro-scale airflow instability (**Figure 6**).

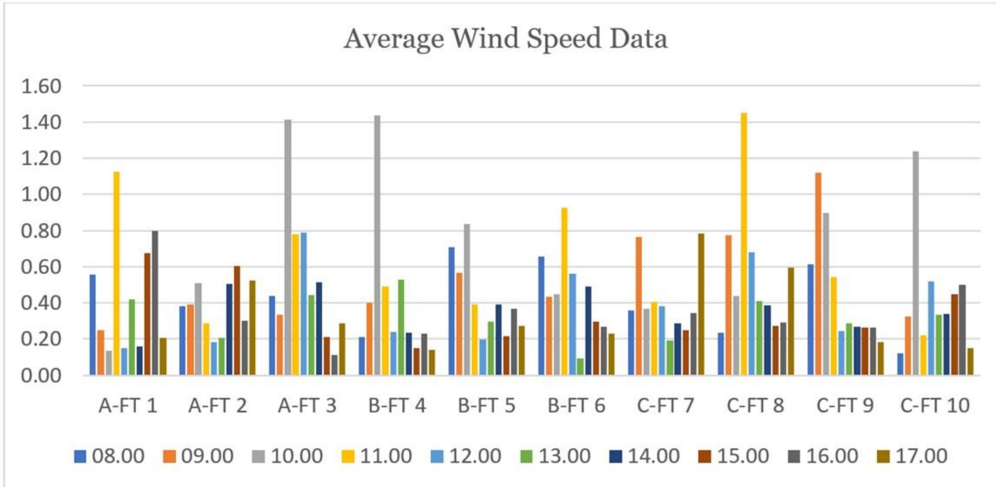

Figure 6. Average Wind Speed Data

The Average Wind Speed Data diagram illustrates the variation in wind velocity across the ten measurement points from 08:00 to 17:00, showing fluctuations strongly influenced by land-cover characteristics and vegetation structure. Overall, wind speeds remain low at several locations, particularly where airflow is obstructed by buildings or dense tree canopies—such as at A-FT2, B-FT5, and C-FT7—which consistently record average values below 0.5 m/s during most measurement hours. In contrast, higher wind speeds are observed at more open sites, including A-FT1, A-FT3, B-FT4, as well as C-FT8, C-FT9, and C-FT10, where peak values occasionally exceed 1.0 m/s, especially around 09:00 and 11:00. These fluctuation patterns confirm that spatial configuration, vegetation density, and surface typology play a central role in regulating airflow, with open areas receiving stronger air circulation compared to locations obstructed by built structures or tree canopies.

The calculation of the Temperature Humidity Index (THI) reinforces these observations. Points with substantial shading and surrounding vegetation, such as A-FT1 and B-FT4, showed THI values between 27.21–27.37°C, categorized as comfortable. By contrast, points dominated by hard surfaces, such as A-FT2, A-FT3, C-FT9, and C-FT10, had THI values above 29°C, falling into the uncomfortable category (**Table 2**).

Table 2. THI Calculation Results at Each Measurement Point

Location	Information	THI	Comfort Criteria
A-FT 1	Shaded Parking Area	27.37	Comfortable
A-FT 2	Exposed Field	29.93	Uncomfortable
A-FT 3	Exposed Pedestrian Paths	29.14	Uncomfortable
B-FT 4	Shaded Pedestrian Paths	27.21	Comfortable
B-FT 5	Moderately Shaded Garden	28.67	Comfortable
B-FT 6	Shaded Garden	27.79	Comfortable
C-FT 7	Shaded Open Area	27.43	Comfortable
C-FT 8	Semi-Shaded Building Area	27.67	Comfortable
C-FT 9	Exposed Parking Area	29.04	Uncomfortable
C-FT 10	Exposed Built-up Area	29.10	Uncomfortable

Table 2 presents the variation in thermal comfort conditions across ten measurement points representing different land-cover characteristics within the Faculty of Engineering area. Points with substantial tree shading—such as A-FT1, B-FT4, B-FT6, C-FT7, and C-FT8—show THI values between 27.21 and 27.79, placing them in the comfortable category. Conversely, sites with open, minimally vegetated surfaces—A-FT2, A-FT3, C-FT9, and C-FT10—record THI values above 29, indicating uncomfortable thermal conditions. Meanwhile, B-FT5 falls near the comfort threshold with a THI of 28.67, suggesting that areas with moderate vegetation still provide noticeable cooling benefits. Overall, the table underscores that vegetation presence and shading intensity are the primary determinants in reducing THI values and improving outdoor thermal comfort across the campus environment.

Comparative analysis shows that thermal comfort varied across the three zones, but not uniformly within each zone. In Zone A, only one point (A-FT1) was categorized as comfortable, while A-FT2 and A-FT3 fell into the uncomfortable category due to exposed surfaces. Zone B exhibited mixed conditions: B-FT4, B-FT5, and B-FT6 were all comfortable, demonstrating that moderate to high vegetation can effectively improve thermal comfort even in semi-open spaces. Zone C also showed a combination of comfort levels; while C-FT7 and C-FT8 remained comfortable due to partial shading, points C-FT9 and C-FT10 were uncomfortable because of direct exposure and extensive hardscape. These findings indicate that thermal comfort is more strongly influenced by localized vegetation density and shading conditions than by zone classification alone, reinforcing previous evidence that hard surfaces intensify heat accumulation while vegetation contributes substantially to microclimatic cooling.

The implications extend beyond climate metrics to campus life. Non-vegetated areas, primarily used for parking and circulation, expose users to higher heat levels. Conversely, green zones serve as cooler, more comfortable areas for rest and social interaction. This confirms a strong relationship between vegetation density, surface type, and thermal comfort in tropical campus environments. Adding trees and green areas in identified hotspots can potentially reduce THI by 1.5–2°C.

Overall, the findings demonstrate that well-planned green open spaces not only enhance aesthetics but also improve the microclimatic comfort of campus environments. This has direct relevance for supporting academic activities and user well-being. Furthermore, the analysis underscores the need for a zoning-based approach that integrates vegetation, surface characteristics, and airflow to optimize thermal comfort. Such an approach provides a scientific basis for sustainable campus development, including decisions on tree planting, garden design, and more climate-responsive hardscape planning. Implementing these strategies in the Faculty of Engineering can substantially improve green space quality while mitigating UHI impacts on campus.

Discussion

The findings of this study are consistent with previous research that highlights the critical role of vegetation in reducing surface temperatures, increasing humidity, and stabilizing wind flows in tropical open spaces. However, the uneven distribution of vegetation across campus remains a major challenge. These results collectively reinforce the need for zoning-based GOS management strategies to achieve optimal thermal comfort. The integration of field data and THI analysis provides a robust basis for formulating recommendations for open space governance on tropical campuses.

More specifically, the distribution of vegetation emerges as a determining factor in shaping microclimatic conditions within the Faculty of Engineering, Syiah Kuala University. Zones with dense vegetation, such as Zone A, consistently recorded lower temperatures and THI values compared to semi-open and built-up areas. These findings reaffirm the established theory that trees with dense canopies can lower air temperatures through shading and evapotranspiration mechanisms [8].

The consistency of these results with previous studies strengthens their validity. For instance, Bambang and Eddy [18] in their study of Taman Srigunting, Semarang, found that areas dominated by vegetation had significantly higher levels of thermal comfort than areas lacking tree cover. In line with these observations, the current study provides additional empirical evidence supporting the crucial role of vegetation in creating cooler and more comfortable microclimates in open spaces.

At the same time, the analysis of Zone B illustrates the nuanced influence of vegetation density and spatial arrangement. Point B-FT4, characterized by shade trees, demonstrated better comfort levels than B-FT5, which had minimal vegetation cover. This contrast emphasizes that not only the quantity but also the spatial distribution and strategic placement of vegetation determine its effectiveness in lowering ambient temperatures.

By contrast, Zone C represents the opposite condition. Here, the dominance of hardscape resulted in increased average temperatures and reduced relative humidity, leading to less favorable microclimatic conditions. This finding aligns with Achmad et al. [1], who showed that the conversion of vegetated land into built-up areas in Banda Aceh contributes to rising surface temperatures and intensifies Urban Heat Island (UHI) effects. The results of the present study can therefore be regarded as additional empirical evidence of UHI dynamics at the campus scale.

Relative humidity patterns further reinforce this relationship between vegetation and thermal comfort. Zones with dense vegetation not only remained cooler but also maintained higher humidity levels, which enhances comfort for users. This result corresponds with the findings of Mala et al. [6] in Manado City, where dense green open spaces were shown to improve humidity and create more comfortable microenvironments. Thus, the dual effect of vegetation—lowering temperature and retaining humidity—confirms its irreplaceable function in tropical climate adaptation.

From the perspective of sustainable campus planning, these findings highlight the urgency of integrating green open spaces into the design of educational areas. The addition of shade trees in semi-open and built-up areas has the potential to reduce THI values by 1.5–2°C, which is a meaningful improvement in humid tropical climates. Such a recommendation is also in line with the ASHRAE 55 [37] thermal comfort standard, which emphasizes adapting outdoor environments to local climatic conditions.

Despite the strong evidence provided, several limitations of this study must be acknowledged. First, the measurements were conducted within specific periods and therefore do not capture seasonal variations. Second, the study did not include detailed assessments of subjective perceptions from campus users, leaving a gap in understanding the relationship between objective thermal comfort and subjective experiences.

Another limitation lies in the lack of detailed mapping of vegetation species contributing to thermal regulation. Previous studies, such as Putra and Ola [15], have shown that certain tree species are more effective in providing shade and influencing wind circulation. Future research should therefore explore species-level effectiveness to identify optimal vegetation strategies for humid tropical climates.

The practical implications of this research are evident. Campus GOS management should adopt a zoning approach that considers vegetation distribution, surface material, and wind-flow patterns simultaneously. These results can serve as the scientific foundation for spatial governance policies oriented toward sustainability and the well-being of the academic community.

Finally, this study opens pathways for further investigation into integrating quantitative and qualitative methods in assessing campus thermal comfort. Combining user perception surveys with simulations of vegetation addition scenarios, for instance, can provide a more comprehensive and multidimensional understanding. In this way, the research contributes not only to academic discourse but also to practical applications in the planning of sustainable tropical campuses.

Conclusion

This study demonstrated that the distribution and availability of green open space strongly influence thermal comfort in the Faculty of Engineering at Syiah Kuala University. Zones dominated by vegetation consistently recorded lower air temperatures, higher relative humidity, and more stable wind flows compared to semi-open and built-up areas. These differences in land cover directly affected the Temperature Humidity Index (THI), which in turn determined the level of thermal comfort experienced by campus users. The results, therefore, highlight a clear relationship between vegetation density, microclimatic parameters, and comfort conditions in a humid tropical campus environment.

Building on these findings, the main implication of this study is the urgent need to adopt a more systematic and equitable green open space management strategy for the campus area. Strategic distribution of trees and vegetation not only reduces localized heat accumulation but also mitigates the impacts of the Urban Heat Island phenomenon. At the same time, the evidence supports the integration of green infrastructure into sustainable campus planning models for tropical climates, aligning environmental management with user well-being.

In conclusion, this research contributes both empirical evidence and practical insights to the discourse on campus spatial governance. It shows that vegetation-based interventions are not merely aesthetic but essential in shaping thermal comfort and supporting the welfare of academic communities. The outcomes of this study can therefore serve as a foundation for policy formulation, campus master planning, and future initiatives aimed at creating a resilient and comfortable educational environment in humid tropical regions.

Acknowledgments

The authors gratefully acknowledge the Department of Architecture and Planning, Faculty of Engineering, Universitas Syiah Kuala, Indonesia, for their support in the completion of this research.

Conflict of Interest

The authors declare no conflicts of interest.

Author Contribution Statement

M. Rafi Farrel: Conceptualization, Writing-Original draft preparation, Investigation. **Cut Nursaniah:** Methodology, Data curation, Supervision. **Laina Hilma Sari:** Software, Validation. **Mirza Fuady:** Writing-Reviewing and Editing, Visualization.

Data Availability Statement

The data used to support the findings of this study are included within the article.

Ethics Approval

Not required.

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