



Urban Microclimate Meets Building Envelope: Infrared Thermography Study of Tropical Campus Tower

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Abstract

Building envelopes in hot-humid tropical climates must maintain thermal comfort and energy efficiency under exposure to solar radiation and urban heat. This study evaluates the thermal behaviour of a 13-storey campus tower in Malang, Indonesia, using Unmanned Aerial Vehicles (UAV) based infrared thermography at three daytime intervals, namely 10.00 a.m., 12.00 p.m., and 2.00 p.m. The surface temperature of the façade was analysed based on its west, north, east, and south orientation, as well as the main materials, which were window glass and plastered and painted brick walls. Additional measurements were taken on the microclimate surface around the building. The results showed that the peak temperature was influenced by orientation. The east façade reached its highest maximum in the morning, max 43.5 °C at 10.00 a.m., while the west façade reached its highest maximum in the afternoon, max 44.9 °C at 2.00 p.m. The south façade recorded the lowest morning minimum, min 22.6 °C at 10.00 a.m. Window glass was generally slightly warmer than the surrounding plaster walls, generally by less than 1 degree Celsius. Outside the building envelope, hard surfaces are significantly hotter, with a peak of 56.5 °C on paver blocks at 12.00 p.m., while vegetation points are lower at around 30 °C to 38 °C. These findings underscore the practical importance of orientation-based shading, glazing control, and environmental heat mitigation, while being supported by limited handheld validation on selected accessible façade surfaces.

Keywords: building envelope, infrared thermography, tropics, microclimate

Iklm Mikro Perkotaan dan Selubung Bangunan: Studi Termografi Inframerah pada Bangunan Tinggi Kampus Tropis

Abstrak

Selubung bangunan di iklim tropis panas-lembap perlu menjaga kenyamanan termal dan efisiensi energi saat terpapar radiasi matahari dan panas perkotaan. Studi ini mengevaluasi perilaku termal kampus 13 lantai di Malang, Indonesia, menggunakan termografi inframerah berbasis *Unmanned Aerial Vehicles* (UAV) pada tiga interval waktu di siang hari, yaitu pukul 10.00, 12.00, dan 14.00. Suhu permukaan fasad dianalisis berdasarkan orientasinya ke barat, utara, timur, dan selatan, serta bahan utama yang digunakan, yaitu kaca jendela dan dinding bata yang diplester dan dicat. Pengukuran tambahan dilakukan pada permukaan mikroklimat di sekitar bangunan. Hasil menunjukkan bahwa suhu puncak dipengaruhi oleh orientasi. Dinding timur mencapai suhu maksimum tertinggi pada pagi hari, maksimum 43.5 °C pada pukul 10.00, sementara dinding barat mencapai suhu maksimum tertinggi pada siang hari, maksimum 44.9 °C pada pukul 14.00. Dinding selatan mencatat suhu minimum terendah pada pagi hari, minimum 22.6 °C pada pukul 10.00. Kaca jendela umumnya sedikit lebih hangat daripada dinding plester di sekitarnya, umumnya kurang dari 1 derajat Celsius. Di luar selubung bangunan, permukaan keras jauh lebih panas, dengan puncak 56.5 °C pada blok paving pada pukul 12.00, sementara titik vegetasi lebih rendah sekitar 30 °C hingga 38 °C. Temuan ini menegaskan pentingnya secara praktis strategi peneduh berbasis orientasi, kontrol kaca, dan mitigasi panas lingkungan, serta didukung oleh validasi handheld terbatas pada permukaan fasad terpilih yang dapat diakses.

Kata Kunci: selubung bangunan, termografi inframerah, tropis, iklim mikro

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Introduction

Multi-story buildings in hot-humid climates, particularly in Indonesia, have challenges in regulating solar exposure all year round. Building characteristics affect the local microclimate, and this condition influences the building's thermal performance and energy efficiency [1], [2]. The Urban Heat Island (UHI) effect and climate change significantly influence building energy usage [3]. Rapid urbanization in developing countries can worsen UHI by increasing urban density, and expanding built-up surfaces, which can reduce outdoor thermal quality [4], while rising urban temperatures increase the building energy demand for air conditioning [5].

Radiation from the sun can pass through multiple stories of a building and increase the heat inside, which can be attributed to the large building envelope. Thus, the building shape becomes a determining factor for the control of the indoor environment [6], while the building envelope serves as a mediator between outdoor and indoor environments, influencing the building's thermal performance [7]. The thermal performance of building envelopes is influenced by key factors such as thermal transmittance (U-value), air leakage, and the selection of high-performance insulating materials [8], [9], [10], [11]. Building envelope characteristics affect indoor and outdoor thermal conditions, contributing to the UHI effect [12], so well-planned building envelopes are effective for mitigating UHI in urban areas [13]. The integration of green infrastructure is a positive addition to the alteration of the surface roughness of the UHI. Increasing vegetation cover can improve the microclimate [14] and reduce air conditioning loads inside buildings [15]. Thermography-based assessment can be used to monitor climatic stress in vegetation and support data-driven evaluation of vegetation performance under environmental loads [16].

Assessing the thermal performance of building envelopes remains a problem despite improved materials and planning. Non-invasive Infrared thermography (IRT) detects heat loss, provides estimates of U-values, and locates thermal bridges for energy efficiency improvements [17], [18], [19], [20]. UAVs have recently been incorporated into IRT, which facilitates and enhances the efficiency of the identification of thermal anomalies over large areas of building envelopes [21], [22]. Building morphology and urban layout affect microclimates by influencing heat absorption, wind flow, and shading, with compact urban forms potentially intensifying the UHI effect [23]. A well-designed urban structure that integrates green areas, varied building heights, and shading can improve energy efficiency and reduce heat retention. Compared to low building areas, densely populated high-rise areas greatly influence the temperature, humidity, and human thermal

comfort [23]. Moreover, building spacing affects natural cooling effects, where closely spaced buildings limit ventilation and increase local temperatures [24]. For energy-efficient construction in urban areas, the right envelope materials are necessary to decrease cooling loads on high-rise buildings. Better insulation materials, especially ones with higher thermal resistance, reduce air conditioning use [11], [25]. Furthermore, materials with additional innovative technologies to manage heat flow can substantially control cooling energy use [26].

The research object is the tallest and one of the largest campus buildings in the hot-humid Malang City, Indonesia. Malang City has undergone dramatic physical changes, especially in the main campus area. The main campus area changes in morphology from a single building to multiple buildings, and the construction of many mid and high-rise buildings increases building density. Before the end of 2019, there were 19 medium-rise buildings of 8 floors and 7 high-rise buildings of 13 floors in the campus area. Ongoing construction in recent years has included multiple high-rise buildings, some of which are the tallest in Malang. The faculty building on campus is 13 stories tall and is the tallest building on campus. It also shows a growing trend of vertically built university buildings in Indonesia. The building has simple finishes, consisting of painted plastered brick walls and glass windows.

This research examines the thermal performance of the building envelope in high-rise university buildings in Indonesia's hot-humid climate. It explores the façades' thermal performance, façades' materials and orientations, and the urban microclimate's influence. The researcher utilizes UAV-based IR to develop thermal maps of the high-resolution micromaps. It is anticipated that the results will assist in the creation of energy-efficient design and smart façades. However, studies using UAV-based infrared thermography (UAV-IRT) on tropical campus high-rise buildings that simultaneously examine façade orientation, envelope materials, and the surrounding microclimate remain limited.

Method

This study adopts a quantitative research methodology. IRT and UAVs are used to measure the thermal performance of the building. This study evaluates the temperature of building façades in relation to the orientation of the building and the materials used to determine the envelope performance in hot-humid climates. The research was conducted on a 13-story building in Malang, Indonesia (7.95°S, 112.61°E). Thermal imaging, microclimatic analysis, and spatial mapping were used to represent a tropical educational building (see Figure 1 and Figure 2). The building was selected for research based on its height, shape, orientation, and materials. The selected

building has a relatively simple envelope composition, consisting mainly of painted plastered brick walls and glass windows, which allows the thermal behaviour of common façade materials in tropical high-rise campus buildings to be clearly observed.

Infrared thermography using the DJI Mavic 3 Thermal Drone captured high-resolution surface temperatures of building façades non-invasively. The UAV-based thermal measurements were conducted under clear-sky daytime conditions at three intervals, namely 10.00 a.m., 12.00 p.m., and 2.00 p.m., to capture diurnal variations in façade surface temperature caused by changing solar exposure. Clear-sky conditions were selected to minimize weather-related disturbances and obtain more consistent thermal readings across façade orientations and surrounding microclimatic surfaces. However, potential biases caused by reflected solar radiation, surface emissivity variation, and transient environmental conditions were considered as methodological limitations of the study.

The observation focused on the upper building envelope, particularly the 11th-floor façade area, and included four façade orientations: west, north, east, and south. In addition to the building envelope, surrounding microclimatic objects were also recorded, including tiled roofs, metal roofs, paver blocks, road surfaces, and vegetation. Previous studies confirm that UAV-mounted thermal cameras provide wider coverage than conventional handheld thermal cameras [21], [22].



Figure 1. The research object: (a) west view; (b) top view



Figure 2. The building elevation: (a) west façade, (b) north façade, (c) south façade, (d) east façade

Thermal imaging was used at three daily intervals to capture diurnal variations in façade surface temperatures [18]. For the purpose of data verification, a thermal imaging drone was calibrated using an Hti HT-A1 thermal imaging camera, with both devices having an emissivity setting of 0.95. An infrared camera was also used to capture surface temperature differences on the wall surface [27]. Thermal imaging data for vegetation, building gaps, and road surfaces were also analyzed to understand the urban microclimate.

These thermal parameters indicate how local microclimatic conditions shape façade surface temperatures and the built environment's thermal performance [28]. Façade temperatures were analyzed by orientation and material to identify thermal anomalies and bridging [29]. Historical climatic data, on-site sensors, and UAV readings were used to ensure accuracy in the thermal data obtained.

Thermographic data were collected in a synchronized and continuous manner to capture transient temperature fluctuations [30]. All drone flights met the regulations of the urban area of the Indonesian civil aviation concerning drone operation. Solar and environmental effects can bias IRT results, so reflected radiation and transient solar impacts were considered in data correction [31]. In simple terms, this method is easy to repeat for checking how efficient a tropical high-rise envelope performs, and it helps guide more sustainable, energy-saving design.

Results

Surface Temperature Variations by Building Façade Orientation

Midday heat shows clearly in Figure 3 through infrared snapshots of the building's façade surfaces. The thermal images indicate that façade temperatures vary greatly depending on the façade orientation,

angle to the sun, and the time of the day. The west-facing façade recorded the highest surface temperatures, that hits 44.9 °C at 2.00 p.m., while the

east-facing façade reached 43.5 °C at 10.00 a.m. before cooling later in the day.

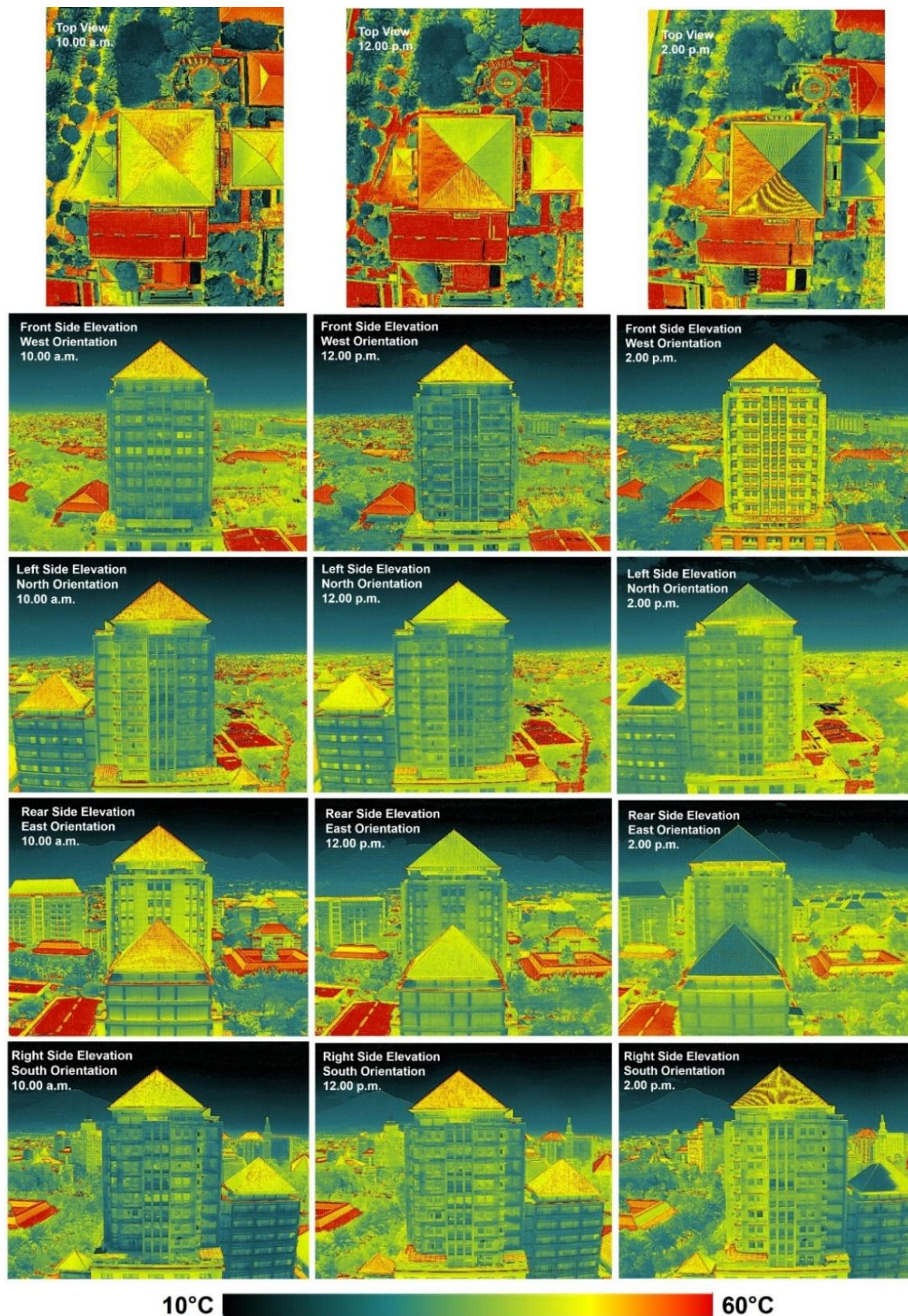


Figure 3. The thermal drone image of the building envelopes at 10.00 a.m., 12.00 p.m., and 2.00 p.m.

Table 1. Average Surface Temperatures on the 11th floor Building Envelope

Façade orientation	Surface temperature (°C)								
	10.00 a.m.			12.00 p.m.			2.00 p.m.		
	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
West	27.5	33.2	30.4	24.4	31.4	27.9	27.5	44.9	36.2
North	26.7	42.3	34.5	31.9	37.2	34.5	29.8	36.8	33.3
East	28.9	43.5	36.2	30.6	35.6	33.1	28.9	33.2	31.1
South	22.6	30.6	26.6	28.0	35.6	31.8	27.2	41.1	34.1

Table 2. Material Surface Temperatures on the Upper Building Envelope

Façade orientation	Surface temperature (°C)					
	10.00 a.m.		12.00 p.m.		2.00 p.m.	
	Glass window	Plastered brick wall	Glass window	Plastered brick wall	Glass window	Plastered brick wall
West	32.3	30.2	29.3	28.4	38.8	38.0
North	31.4	29.8	35.2	34.3	33.2	32.3
East	36.4	35.6	34.3	33.2	30.2	30.6
South	27.2	26.7	33.2	31.9	32.3	32.7

Table 3 Surface temperatures surrounding the building

No	Material/Object	Measurement area/point	Position from the building	Surface temperature (°C)		
				10.00 a.m.	12.00 p.m.	2.00 p.m.
1	Building object - tiled roof	Area	Top	45.1	50.8	46.6
2	East building - tiled roof	Area	East	45.5	52.0	43.4
3	South building - metal roof	Area	South	50.7	55.5	45.9
4	Parking area - paver blocks	Point	West	44.5	56.5	55.2
5	Road - paver blocks	Point	West	46.4	55.9	40.8
6	Small tree	Point	West	31.4	38.4	37.6
7	Big tree	Point	North	30.2	37.6	37.2

As indicated in Table 1, the west-facing façade recorded the highest average temperature at 36.2 °C at 2.00 p.m., whilst the east-facing façade was slightly cooler at 31.1 °C. In contrast, the south-facing façade that receives less sun in the mornings recorded the coolest temperature at 22.6 °C at 10.00 a.m. These trends are also apparent in the thermal images, which confirm that façade orientation has a significant effect on heat retention, which is critical to the discussion on energy efficiency in hot-humid climates. Additionally, the roof experienced significant heat gain at midday and 2.00 p.m., which suggests high solar energy absorption due to low surface reflectance or thermal mass.

Based on Table 2, the window glass surface was generally slightly warmer than the adjacent plastered and painted brick walls, typically by less than 1 °C across orientations and measurement times. However, some window sections with internal blinds were warmer than the plastered and brick walls, perhaps due to different thermal characteristics. Additionally, the elevated temperature observed in the wall sections between the windows and in some structural elements may indicate localized heat accumulation or possible thermal anomalies in those areas. However, these patterns should not be interpreted as definitive evidence of poor insulation or thermal bridging, since detailed envelope diagnostic testing was not conducted in this study.

Thermal imaging data were validated using an Hti HT-A1 handheld thermal imaging camera on selected

accessible plastered wall surfaces of the north façade only, due to site access and operational safety constraints. The validation was conducted at the same observation times as the UAV-based IRT acquisition, namely 10.00 a.m., 12.00 p.m., and 2.00 p.m. The handheld and UAV-derived surface temperature readings showed a high level of agreement, with an average difference of 0.53%. Therefore, the validation supports the reliability of UAV readings for selected accessible façade surfaces, rather than representing full validation across all building façades.

Overall, UAV-based infrared thermography was consistent with established thermal transmittance models, and the data were further refined using corrective algorithms to account for emissivity variations [30]. West-facing façades showed the highest heat accumulation, underscoring the need for effective shading. The validated UAV data confirm façade orientation as a key passive cooling strategy for energy-efficient design in hot-humid climates.

The Impact of Building Envelope Materials

As shown in Table 2, glass window surfaces were generally slightly warmer than adjacent plastered brick walls, mostly by less than 1 °C, although some orientations showed different patterns. Therefore, the material-related temperature differences should be interpreted cautiously, as they may also be influenced by solar exposure, optical properties, emissivity, airflow, and indoor conditions. The glass pane in the west-facing window reaches its maximum

temperature of 38.8 °C at 2.00 p.m., and the brick face hits at 38.0 °C. This explains the intense solar radiation in the afternoon. Conversely, the glass is at 36.4 °C in the east-facing window in the morning, and then cools in the afternoon, with the North-facing window achieving its peak temperature at noon, and the South-facing window cools in the morning and then warms throughout the day. The north-facing glazing would benefit from improved solar control glazing or shading to reduce midday heat; and better glazing, as well as the more suitable choice of materials in the right orientation, encourage a reduction in energy waste through improved thermal comfort. These orientation driven differences are consistent with field evidence that glazing can reach higher peak temperatures than masonry and that peak surface temperature can vary substantially by orientation under solar exposure [12]. Reflective coatings may lower façade surface temperatures, although reductions are often modest and depend on conditions [13]. In contrast, brick with an outer finish tends to show more stable thermal behavior due to higher thermal inertia and its capacity to store and release heat over time, which can delay and smooth temperature fluctuations [12]. External shading is also widely recognized as a necessary passive measure to reduce solar heat gains and support lower cooling loads [12]. Passive cooling to improve thermal comfort and mitigate UHI can be enhanced through thermal mass and solar control (shading and glazing), with UAV thermography used to assess façade material performance.



Figure 4. The points and areas of surface temperature surrounding the building

Microclimatic Influence on Thermal Performance

Heat retention also is affected by microclimatic components such as open spaces, surface types, and vegetation. For example, urban heat load is high in denser built-up urban areas without vegetation. On the other hand, a built environment with vegetation is more effective in cooling the façade. As shown in Table 3 and Figure 4, temperature variations align with surrounding features like rooftops, parking areas, and vegetation, highlighting their impact on the microclimate. These findings emphasize the need to integrate microclimatic considerations into building and urban design strategies. The parking area west of the building, covered with paver blocks, registered peak temperatures of 56.5 °C at 12.00 p.m., as shown in Table 3. The paver blocks road surface, especially to the west of the structure, displayed comparably elevated temperatures, with measurements of 55.9 °C. The elevated temperatures surrounding the building, as depicted in the thermal photos, enhance heat absorption by the structure, especially through the west-facing façade.

On the contrary, the areas with greenery, including the small west-side tree and the larger north-side tree, had a measurable cooling impact on the surrounding areas. Here, the north-side tree area recorded a surface temperature of 37.2 °C, and the west-side tree area recorded a temperature of 37.6 °C, demonstrating that even the smallest greenery can have a measurable cooling effect. These findings illustrate that the landscaping and environmental features surrounding a building play a significant role in managing surface temperatures of the building façades and can positively impact the energy performance of the building.

From the aerial thermography data, paver blocks that were shaded by tree cover had a surface temperature of 40.8 °C, while in the parking lots, the unshaded paver blocks reached a surface temperature of 55.2 °C at 2.00 p.m. This clearly demonstrated that greenery surrounding the building and the shading system of the building strongly influence surface heating. Dense greenery and vertical greening systems can lower façade temperatures, with reported daytime reductions in the range of 4–12 °C, depending on vegetation and substrate characteristics [13]. Tree shading also contributes to cooling by reducing direct solar exposure on surrounding surfaces [24]. Together, vegetation and shading work synergistically as passive measures to limit heat accumulation and support UHI mitigation [13]. Urban form further shapes thermal conditions: compact morphologies tend to suppress wind speed and intensify heat retention, whereas more open layouts support better heat dissipation through airflow [5]. The condition of ground surfaces affects the distribution of surface temperatures around the

building more than any other element there. In this study, most of the concrete paver blocks recorded extremely high temperatures, above 56.5 °C, midday, particularly in the positions vertically above the blocks, due to solar radiation. In contrast, the ground surface temperatures in areas with vegetation were significantly lower. This shows the extent to which Vegetation cover can help reduce local heat build-up and thermal stress in the surrounding outdoor environment through shading and evapotranspiration [13].

The findings show that the east façade experienced higher surface temperatures in the morning, while the west façade became the hottest in the afternoon, reflecting the influence of solar orientation. Glass surfaces were generally only slightly warmer than plastered brick walls, mostly by less than 1 °C, so this difference should be interpreted cautiously. In contrast, hardscape surfaces such as paver blocks and roads were substantially hotter than vegetated areas, indicating the stronger role of surrounding microclimate and shading in reducing surface heat accumulation.

Most importantly, this study emphasizes the significance of microclimatic techniques such as vegetation, building spacing, and surface material selection to maximize thermal comfort and energy conservation, especially in tropical climates. Passive cooling techniques are particularly important in the heat confinement around buildings, and in this case, they would significantly reduce the energy demand, which is especially relevant in cooling. UAV-based thermography used in this study can be relied upon to implement and evaluate the strategies in question, and it can be offered as proof for the implementation of extreme climatic responsive design.

Discussion

The findings suggest that thermal performance in hot-humid tropical high-rise buildings is primarily shaped by the interaction between façade orientation, material response, and microclimate exposure. In practice, this implies that east and west-facing façades should be treated as priority zones for solar-control measures, where shading and suitable glazing specifications are likely to deliver the most immediate comfort and cooling-demand benefits [12], [13]. Practically, these findings highlight the need to prioritize shading on the east and west façades, improve solar control for glazing areas, increase tree shading and vegetation around the building, and reduce exposed heat-retaining hardscape surfaces such as paver blocks.

The findings of this study are not intended to be generalized to all tropical buildings. Instead, they provide empirical indications for campus high-rise buildings with similar characteristics, particularly

buildings with strong façade orientation effects, a simple envelope composition of glass windows and painted plastered brick walls, and dense urban surroundings.

This study has several limitations. First, the thermal measurements were conducted at only three daytime intervals, namely 10.00 a.m., 12.00 p.m., and 2.00 p.m., within a limited observation period; therefore, the results represent short-term daytime thermal conditions rather than long-term seasonal performance. Second, handheld thermal validation was conducted only on selected accessible surfaces of the north façade due to site access and operational safety constraints, so it should not be interpreted as full validation across all building façades. Third, this study focused on exterior surface temperatures and did not include indoor temperature measurements, occupant thermal comfort assessment, or actual energy-consumption data. Finally, although the measurements were conducted under clear-sky conditions, the results may still be influenced by transient environmental factors, reflected solar radiation, and surface emissivity variations.

Future research should explore cost-effective solutions that can balance the initial investment with long-term sustainability, especially for implementation in real projects. This discussion also shows that several factors, such as façade orientation, material selection, shading strategies, urban form, and the use of thermal imaging technologies, are related to each other and should not be considered separately. Therefore, their strategic integration is important to optimize thermal performance, reduce cooling loads, and improve indoor comfort in high-rise buildings located in hot-humid climates.

Conclusion

This research study demonstrates that for high-rise buildings located in hot-humid region, the most significant factors to consider for improving thermal performance and energy efficiency are building orientation, choice of materials, design strategies of building envelopes, and urban morphology. The most optimally designed building orientation allows for the reduction of direct solar gain, which ultimately leads to less cooling load requirements and improves indoor comfort. The UHI effect can also be mitigated, and surface temperatures can be managed with the use of thermal mass, as well as passive cooling techniques, vegetation, and shade structures. In addition, the use of UAV-based IRT for this study has proven to be an effective method of assessing the building envelope, as it provides a means to ascertain the existence of thermal deficiencies within the envelope in an actual condition. The results also provide passive design strategies with empirical evidence for the tropical setting, thereby furthering the discipline of sustainable architecture and urban planning. A more

integrated approach seems apparent using a combination of advanced thermal imaging techniques, envelope design and materials, and spatial planning. Future research should conduct multi-day or seasonal thermal measurements, integrate indoor temperature and occupant comfort data, and include energy consumption or cooling-load simulation to better understand the relationship between exterior surface temperature, indoor thermal performance, and building energy efficiency.

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Declaration of Generative AI

The authors used generative AI tools to assist in drafting and language improvement. All outputs were carefully reviewed, revised, and validated by the authors. The authors take full responsibility for the content of this manuscript.

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