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URBAN MORPHOLOGY AND PASSIVE DESIGN: STRATEGIES TO MITIGATE URBAN HEAT ISLAND AND IMPROVE THERMAL COMFORT IN KUALA LUMPUR

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Abstract

Rapid urbanization in Kuala Lumpur has intensified the Urban Heat Island (UHI) effect, compromising thermal comfort and increasing environmental stress. This study examines how urban morphology and passive building design influence microclimatic conditions in three contrasting areas: Kampung Baru (suburban), Bukit Bintang (dense urban), and KLCC Park (green zone). Field measurements of air temperature, relative humidity, wind speed, and PM2.5 were collected using mobile equipment. Results show that compact urban districts experience elevated temperatures and reduced ventilation, while vegetated and water-adjacent areas provide notable cooling. Findings are evaluated against thermal comfort benchmarks (ASHRAE 55; MS1525), underscoring the need for climate-responsive urban planning. Mitigation strategies include expanding green infrastructure, applying reflective materials, and strengthening passive design features to enhance thermal comfort in high-density tropical cities. The study acknowledges limitations of short-term mobile measurements and recommends future research involving long-term monitoring and simulation modeling to strengthen understanding of UHI dynamics.

Keywords: Urban Heat Island, Thermal Comfort, Urban Configuration, Urban Microclimate, Green Building Design

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INTRODUCTION

Kuala Lumpur, Malaysia's rapidly growing capital, has seen major land use and population increases over the past five decades. This growth has made it one of Southeast Asia's most urbanized cities, but also brought challenges such as the Urban Heat Island (UHI) effect, air pollution, and thermal discomfort (Wang et al., 2019). Rapid urban development has altered the city's microclimate, creating risks for both the environment and human health (Yola, 2018; Ibrahim et al., 2014). The Urban Heat Island (UHI) effect occurs when urban areas are hotter than nearby rural regions due to vegetation loss and the use of heat-retaining materials like concrete and asphalt (Rajagopalan et al., 2014). As green space decreases and built-up areas expand, Kuala Lumpur's ability to regulate temperature weakens, intensifying UHI and reducing environmental resilience (Harun et al., 2020).

Anthropogenic heat from transport, industry, and building energy use raises urban temperatures while releasing greenhouse gases like CO₂ and methane, which trap heat and intensify the UHI effect. Open burning and deforestation further add to this problem (Elsayed, 2012; Malaysian Meteorological Department, 2009). Urban morphology strongly influences heat distribution. Tall buildings and narrow streets create urban canyons that trap heat and block air circulation. These canyons absorb and re-radiate long-wave heat, reducing natural ventilation and limiting nighttime cooling, which raises surface and air temperatures (Rajagopalan, Lim & Jamei, 2014).

The UHI effect is a major global issue, especially in tropical cities like Kuala Lumpur. Higher thermal loads increase heat stress and energy demand for cooling (Elsayed, 2012), while long-term exposure raises risks of heatstroke, respiratory illness, and cardiovascular problems, particularly for vulnerable groups such as children, the elderly, and people with pre-existing conditions (Mohajerani, Bakaric & Jeffrey-Bailey, 2017; United States Environmental Protection Agency, 2020; Shahmohamadi et al., 2011). Urban vegetation is a key mitigation strategy. Parks, urban forests, and rooftop gardens reduce surface and air temperatures through shading and evapotranspiration (Yoshida et al., 2015; Marando et al., 2022). Increasing greenery also improves thermal comfort, lowers pollution, and reduces cardiovascular-related mortality (Shen & Lung, 2016; Devi Kanniah, 2017). The placement and design of green spaces are critical for shaping microclimates.

Material properties also affect UHI. Construction materials with high heat absorption, such as pavements and dark roofs, intensify localized warming (Sreedhar & Biligiri, 2016; Li, 2015). In contrast, cool pavements and reflective surfaces help lower temperatures and improve comfort (Senevirathne et al., 2021; Mohajerani et al., 2017). Malaysia's urban policies now promote sustainability, with tools like the Green Building Index (GBI) encouraging energy efficiency,

natural ventilation, and thermal comfort in climate-responsive development (GBI Township Tool, 2017).

Urban Heat Island (UHI) has become a growing concern in rapidly urbanizing cities. While many studies have examined UHI in temperate regions, there is still limited research on UHI dynamics in tropical cities like Kuala Lumpur, particularly regarding how urban morphology, wind flow, and air quality interact to influence microclimatic conditions.

This research addresses these gaps by examining how wind speed, temperature, and UHI intensity vary across different urban forms in Kuala Lumpur. It also assesses the relationship between PM2.5 levels, air quality, urban morphology, and vegetation to better understand microclimatic impacts. In addition, the study identifies key urban design factors that can help mitigate UHI while improving thermal comfort. Finally, it provides evidence-based recommendations to support sustainable and climate-responsive urban design in Malaysia.

This study builds on past research by analyzing urban, suburban, and green areas in Kuala Lumpur using field data on temperature, humidity, and wind. It shows how urban form shapes microclimate, thermal performance, and UHI effects, aiming to guide planning and passive design strategies that improve comfort and reduce energy use for sustainable city design.

Passive design strategies play a key role by enhancing ventilation and lowering heat. Building orientation, façade design, openings, and layouts that follow wind paths or improve sky view factors can reduce heat buildup and improve airflow (Aflaki et al., 2015; Siew et al., 2011; Gonzalez-Longo & Mohd Sahabuddin, 2019; Zhang et al., 2022; Choi et al., 2018). Courtyards, light-wells, and shading devices also help cut solar gain and support thermal comfort (Yola, 2020; Sahabuddin & Gonzalez-Longo, 2017).

Case Study Areas, Methodology and Limitations

This study examines three sites in Kuala Lumpur: Kampung Baru (low-rise suburb beside high-rises), Bukit Bintang (dense commercial zone), and KLCC Park (green space with vegetation and water). These locations represent different urban forms, enabling comparison of how built form and greenery influence microclimate and the Urban Heat Island (UHI) effect (Figure 1). The goal is to understand how planning and physical features shape thermal conditions and to test passive strategies such as shading, orientation, façade design, and spatial layout for UHI reduction. Mobile measurements of temperature, humidity, wind speed, and PM2.5 were taken at two points per site—one green and one urban—under different routes, weather, and times of day. While mobile data collection has limits, such as short-term weather effects and handling errors, it still provides

valuable fine-scale insights into pedestrian-level microclimate, complementing broader meteorological data.

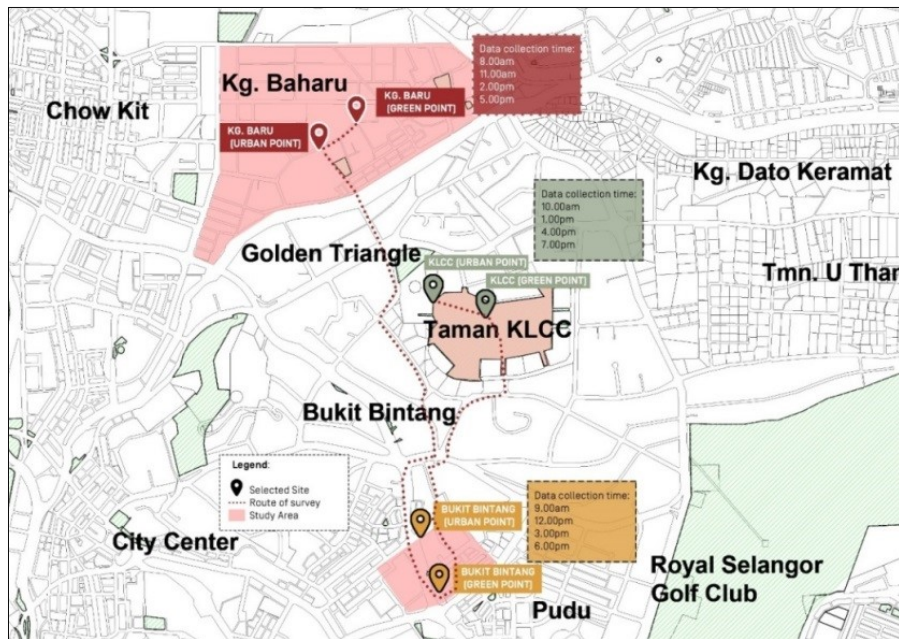


Figure 1: Location of the mobile measurement survey routes during data collection

Requirements for Thermal Comfort

In Malaysia, thermal comfort and indoor air quality (IAQ) are regulated by MS1525, which follows the ASHRAE 55 guidelines (Turner et al., 2010). For Kuala Lumpur's climate, the recommended comfort range is 24–28°C air temperature, 40–70% relative humidity, and 0.15–0.50 m/s wind speed. Air quality is also critical, with the WHO Air Quality Guidelines (2021) setting PM_{2.5} limits at <25 µg/m³ annually and <50 µg/m³ for 24-hour exposure to reduce health risks (Table 1).

Table 1: Parameters, limits and requirements of thermal comfort and IAQ

Parameters	ASHRAE 55 (2013)	MS1525 (2014)
Air Temperature	24.0 -28.4°C	24 -26°C
Relative Humidity	<65%	50-70%
Wind Speed	0.15 -0.8 m/s	0.15 -0.5m/s
PM _{2.5} , WHO standard	annual < 25 µg/m ³ and 24-hour limits < 50 µg/m ³	

IN-SITU FIELDWORK MEASUREMENTS

Key climatic parameters measured at all sites included air temperature, relative humidity, wind speed, and PM2.5, with surface temperature derived to analyze thermal patterns. Data were collected using a PMS5003 Air Quality Monitor and a Digital Anemometer Thermometer through mobile surveys in Kampung Baru, Bukit Bintang, and KLCC Park at different times of day to capture diurnal variations.

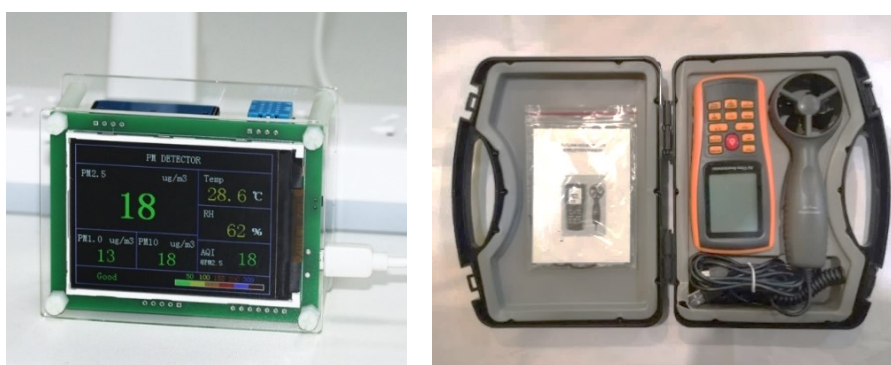


Figure 2: PMS5003 Particulate Matter (PM) Detector Air Quality Monitor Thermometer and Digital Air Flow Anemometer

Measurements were conducted over six days in November 2021 and February 2022, covering both weekdays and weekends, using handheld equipment to record real-time conditions (Figure 2). All surveys followed the ASHRAE research protocol, with instruments placed at pedestrian level (1.1–1.5 m) for outdoor comfort studies (ASHRAE, 2017). Equipment was calibrated before fieldwork, and spot checks were performed during data collection to minimize drift and handling errors.

Data were collected at three sites in Kuala Lumpur: Bukit Bintang (urban), Kampung Baru (suburban), and KLCC Park (green). Six settings were studied, including high- and low-rise housing in Kampung Baru, high- and low-density roads in Bukit Bintang, and hard and soft surfaces in KLCC Park. These site conditions affect temperature, humidity, wind speed, and PM2.5, depending on vegetation, materials, and ventilation.

Measurements in November and February captured seasonal variation during the Northeast Monsoon, which brings high humidity, rainfall, and flooding (Malaysian Meteorological Department, 2020). Kuala Lumpur's hot and humid rainforest climate further intensifies the UHI effect, especially in dense, low-vegetation areas (Ghaffarianhoseini et al., 2019).

Weather patterns also shaped results. In November, Day 1 was sunnier with higher temperatures, while Days 2 and 3 were cloudy and cooler. In February, all three days were cloudy, but Day 2 recorded lower midday temperatures due to heavy rain. Afternoon (2:00–4:00 PM) readings were higher on sunny November days, while evening (5:00–7:00 PM) temperatures in both months were consistent under cloudy or rainy conditions.

FINDINGS

Air Temperature

During the study period, Kuala Lumpur recorded average maximum and minimum temperatures of 32.3°C and 24.7°C in November, and 31.0°C and 23.3°C in February, showing seasonal differences of about 1.3–1.4°C (Meteorological Terminal Air Report, 2021; 2022). These variations also affected humidity and wind speed. As shown in Figures 3 and 4, the lowest temperatures were measured at Kampung Baru green point and KLCC Park (24.3–26.5°C in November; 22.6–23.6°C in February), reflecting the cooling influence of vegetation and water.

By contrast, Kampung Baru's high-rise residential area recorded the highest temperatures, even surpassing Bukit Bintang. In November, temperatures reached 32.0°C in Kampung Baru compared to 29.0°C in Bukit Bintang. This is linked to the "canyon effect" caused by compact low-rise buildings surrounded by high-rises, which trap heat and restrict airflow, consistent with Tumini (2015). Elevated heat may also stem from nearby infrastructure, especially the Ampang–Kuala Lumpur Elevated Highway (AKLEH), where heavy traffic and dense development generate anthropogenic heat and pollutants (Ramakreshnan et al., 2019). With over 26 million vehicles annually and planned future expansion, the AKLEH further contributes to localized warming (Ministry of Works Malaysia, 2015).

ASHRAE 55 sets the comfort range at 24–28.4°C (Turner et al., 2010). While most readings in Kampung Baru, Bukit Bintang, and KLCC Park were within this range, urban points in Kampung Baru and Bukit Bintang often exceeded 28°C in the afternoon. Green areas, trees, and water bodies lowered temperatures by up to 2.2°C, highlighting their role in improving comfort.

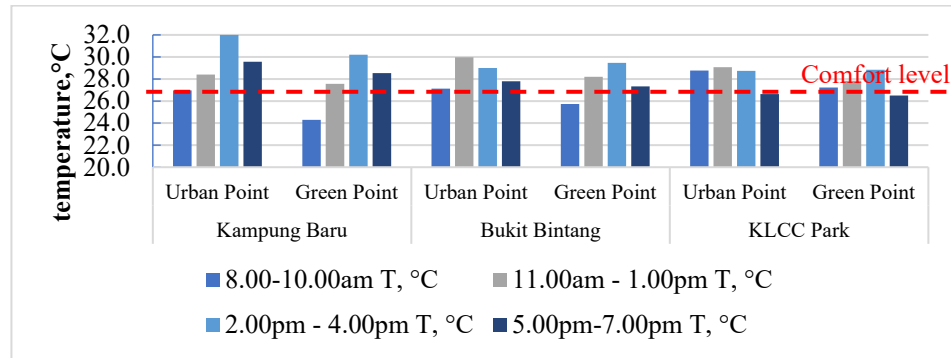


Figure 3: Results of Average Air Temperature in November

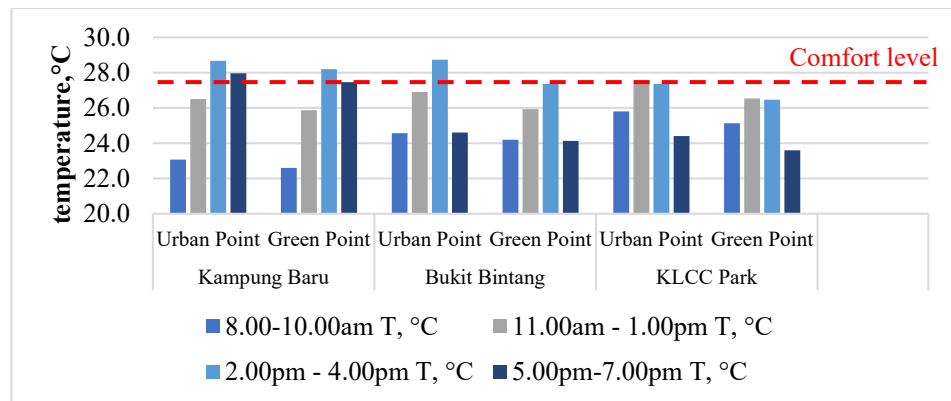


Figure 4: Results of Average Air Temperature in February

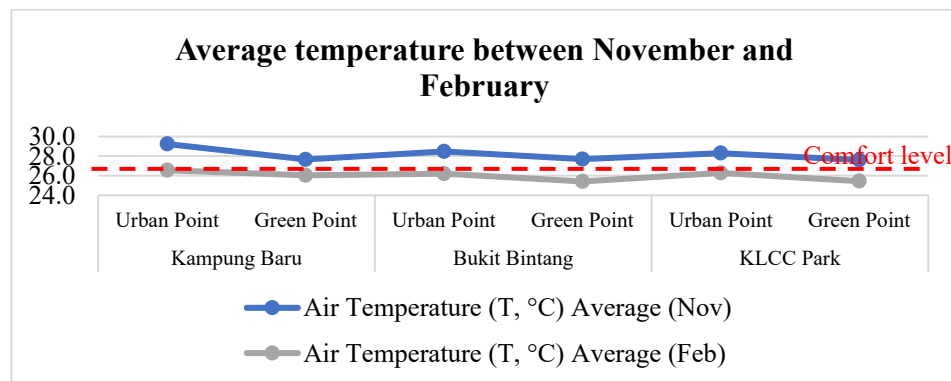


Figure 5: Average Air Temperature between November and February

Relative Humidity

The Malaysia Meteorological Department reported average relative humidity (RH) of 56% in November and 88% in February, due to persistent rainfall (Meteorological Terminal Air Report, 2021). RH is the ratio of water vapor in the air to its maximum capacity at a given temperature and pressure (Yahia, 2019; Djamila, Chu & Kumaresan, 2014). Figures 6–7 show the lowest RH (60–63.7%) in November at 2:00–4:00 PM in Kampung Baru and Bukit Bintang, while the lowest in February was 80.2% in Bukit Bintang. Early mornings had higher humidity: 70.0–87.3% (November) and 85.3–94.3% (February). This increase is linked to evaporative cooling, where water vapor from surfaces and vegetation raises humidity (Procházka et al., 2011).

Afternoon readings showed lower RH as higher temperatures reduced vapor pressure, intensifying the UHI effect. RH decreases as temperature rises (Clausius-Clapeyron relation), showing a negative correlation with UHI intensity (Kamma et al., 2020; Anibaba et al., 2019). Figure 8 shows an 11.8–13.6% RH difference between November and February, mainly due to heavier rainfall. For comfort, ASHRAE 55 recommends RH below 65% (Turner et al., 2010). High RH can lead to mold, while very low RH (<30%) causes discomfort (Djamila, Chu & Kumaresan, 2014). Green points in Kampung Baru, Bukit Bintang, and KLCC Park recorded higher RH than urban points (Figure 8), confirming that vegetation and water bodies raise humidity and provide cooling benefits (Du et al., 2021).

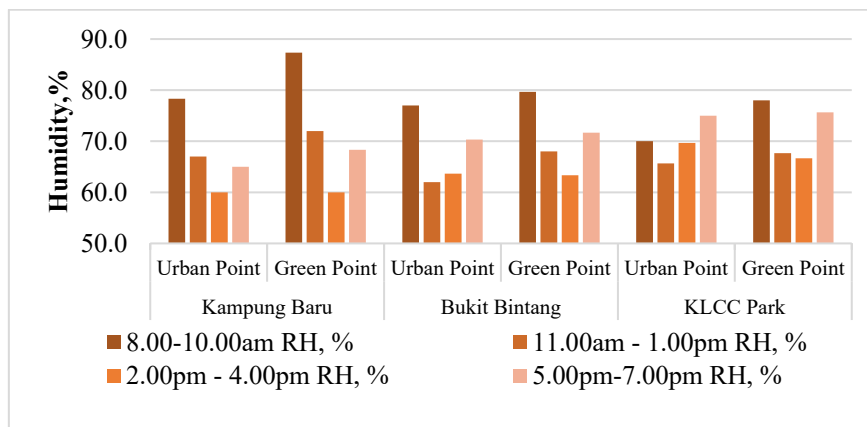


Figure 6: Results of Average Relative Humidity in November

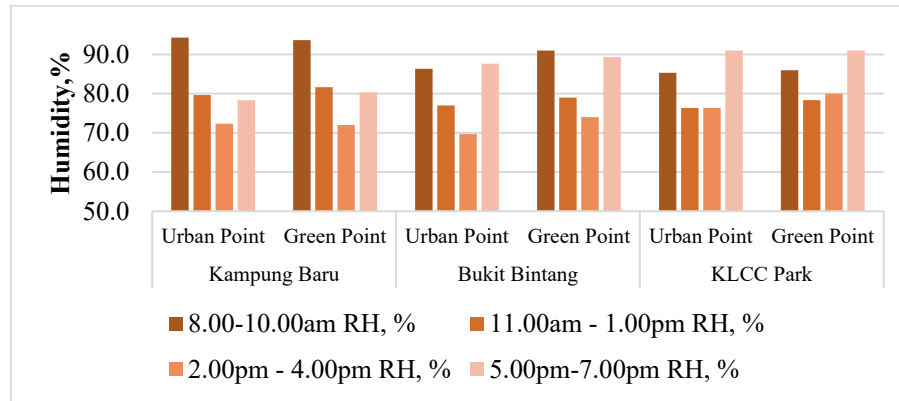


Figure 7: Results of Average Relative Humidity in February

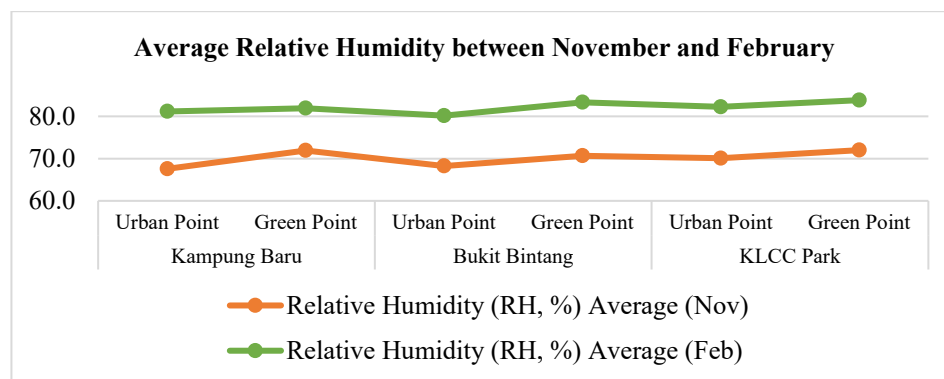


Figure 8: Average Relative Humidity between November and February

Wind Speed

In urban areas, wind speed affects health, thermal comfort, air quality, and UHI intensity more than ambient climate conditions (Anibaba et al., 2019). UHI formation occurs when surfaces release heat slowly under moderate wind conditions (Harun et al., 2020). The Malaysia Meteorological Department reported average wind speeds of 1.8 m/s in November and 1.6 m/s in February, with prevailing winds from the west in November and east in February (Meteorological Terminal Air Report, 2021).

Figures 9–10 show wind speed data for Kampung Baru, Bukit Bintang, and KLCC Park, recorded with a Digital Air Flow Anemometer. Higher wind speeds appeared near high-rises, water bodies, and landscaped areas, as building height and form influence airflow (Rodzi, Razak & Zaki, 2015). However, wind-blocking structures create “wind shadows,” reducing ventilation and pedestrian comfort (Mironova, 2020).

Measured wind speeds were 0.8–1.3 m/s, slightly below the city’s average, due to frictional drag from dense high-rise buildings (Gamesby, 2020). As expected, urban areas are less windy than rural surroundings (National Meteorological Library, 2019). Figure 11 shows that wind speeds ranged from 0.5–1.0 m/s in November and 0.1–0.3 m/s in February, with lower February values linked to rainy conditions.

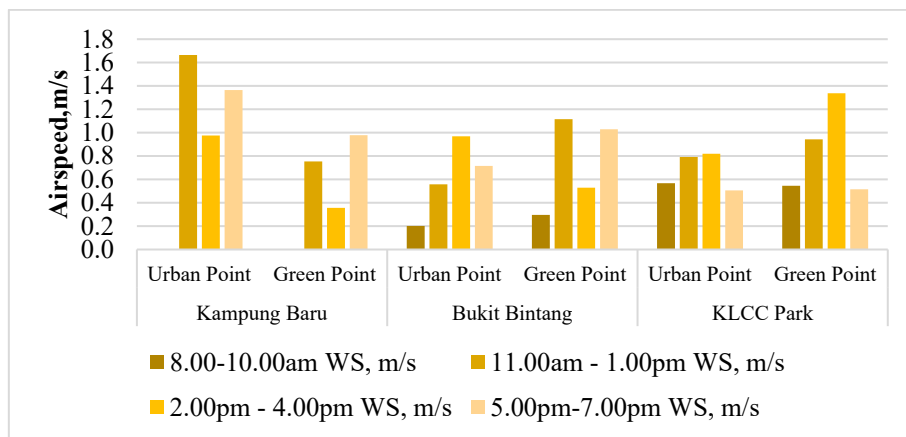


Figure 9: Results of Average Wind Speed in November

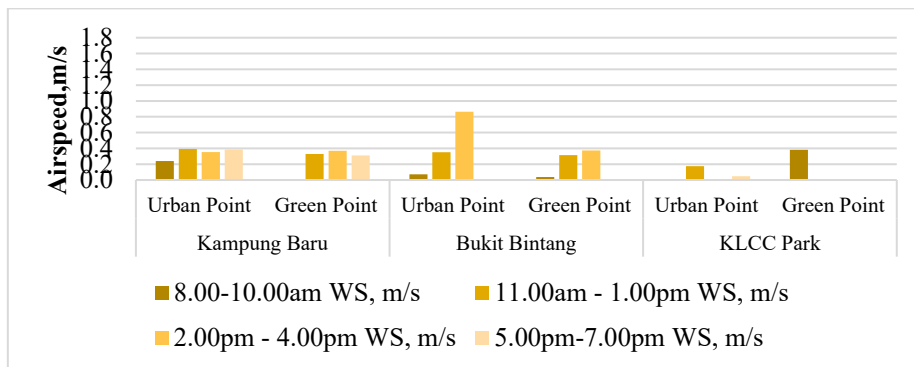


Figure 10: Results of Average Wind Speed in February

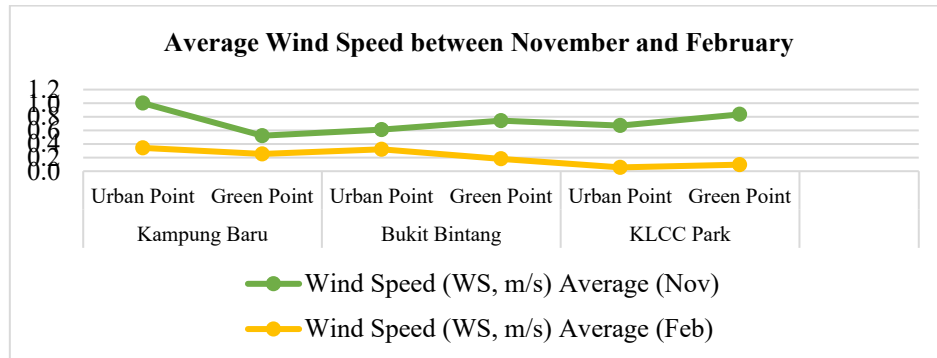


Figure 11: Average Wind Speed between November and February

In Kuala Lumpur, southwest winds are partly blocked at Kampung Baru by high-rises, causing stagnant air and discomfort. Yet, building corners and street canyons increase local wind speeds, with tall structures drawing winds downward. Stronger airflow helps reduce UHI by improving ventilation (Setio et al., 2020; Anibaba et al., 2019).

Particulate Matter (PM2.5)

Figures 13 and 14 show PM2.5 readings at Kampung Baru, Bukit Bintang, and KLCC Park. The highest levels were recorded at Bukit Bintang urban point (27.3 $\mu\text{g}/\text{m}^3$ in November, 26.3 $\mu\text{g}/\text{m}^3$ in February), linked to dense human activity, traffic, and commercial development (Wang, Guo & Han, 2021).

In contrast, KLCC Park green point showed the lowest PM2.5 levels (12.1 $\mu\text{g}/\text{m}^3$ in November, 16.8 $\mu\text{g}/\text{m}^3$ in February). This is due to dense vegetation and water bodies, which help filter air pollutants, absorb emissions, and reduce UHI impacts (Hewitt, Ashworth & MacKenzie, 2020). This underlines the need for green infrastructure in urban planning and building design.

Figures 15 confirms that all PM2.5 levels were below the Malaysian Ambient Air Quality Standard limit of 35 $\mu\text{g}/\text{m}^3$ (Department of Environment, 2020). However, average levels were higher in February (Figure 18), mainly due to rainy conditions. During rain and high humidity, incomplete combustion from vehicles increases PM2.5 emissions (Zalakeviciute, López-Villada & Rybarczyk, 2018). The highest February values were again at Bukit Bintang, emphasizing how traffic congestion and humidity together raise PM2.5 concentrations.

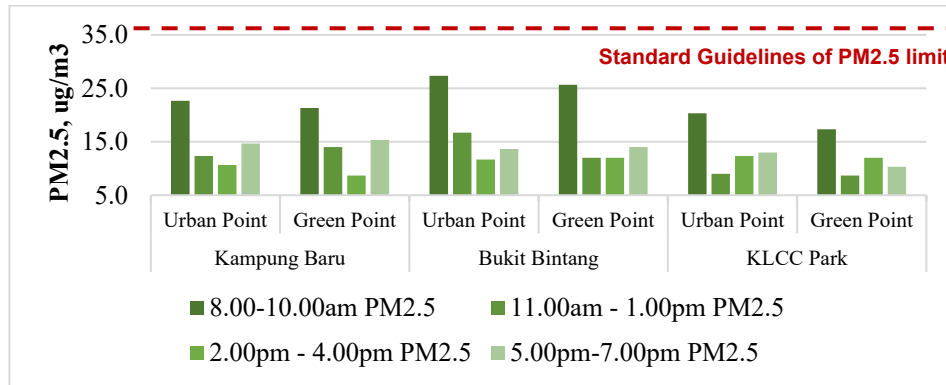


Figure 13: Results of Average Particulate Matter, PM 2.5 in November

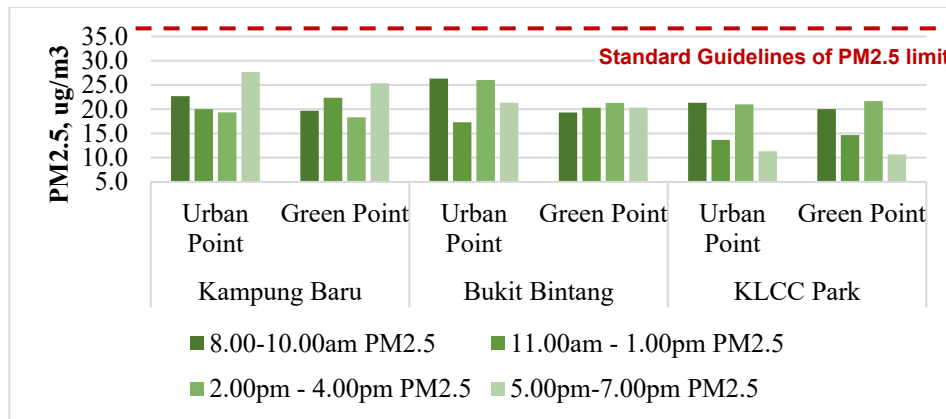


Figure 14: Results of Average Particulate Matter, PM 2.5 in February

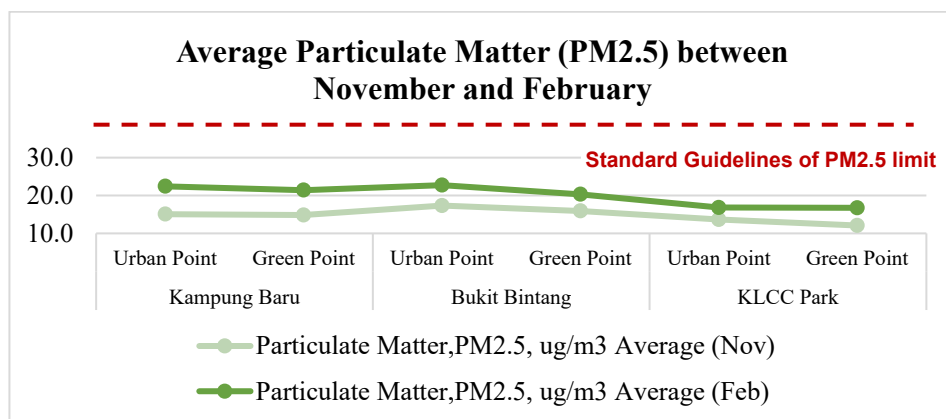


Figure 15: Average Particulate Matter, PM2.5 between November and February

DISCUSSION

The results show clear impacts on pedestrian and occupant comfort. In Kampung Baru and Bukit Bintang, afternoon temperatures often exceeded the ASHRAE 55 comfort limit of 28°C (Turner et al., 2010), with humidity above 65%, creating severe discomfort for vulnerable groups such as children, the elderly, and those with health issues (Shahmohamadi et al., 2011; United States Environmental Protection Agency, 2020). Prolonged exposure raises risks of heat stress, reduced productivity, and higher reliance on air-conditioning.

These findings highlight the need to apply passive design in practice. Roadside trees, shaded walkways, high-albedo façades, and reflective pavements can improve comfort in dense districts, while green roofs provide cooling where space is limited. In residential areas like Kampung Baru, orientation, courtyards, light-wells, and aligned openings can lower indoor cooling loads and improve outdoor airflow (Aflaki et al., 2015; Gonzalez-Longo & Mohd Sahabuddin, 2019).

By linking field measurements with human comfort standards, the study underlines the importance of pedestrian-scale interventions and climate-responsive planning policies. These measures not only mitigate UHI but also support urban livability by making streets, open spaces, and buildings more thermally comfortable.

Table 2: Passive Design Strategies for UHI Mitigation and Thermal Comfort

Category	Strategies	Benefits
Green Infrastructure	Parks, trees, green roofs, rooftop gardens, shaded walkways	Cooling through shade/evapotranspiration, lowers temperatures, better comfort
Reflective Materials	High-albedo façades, cool roofs, reflective pavements	Less heat absorption, cooler surfaces, improved indoor/outdoor comfort
Building Orientation	Align with wind, façade treatments, operable windows, cross-ventilation	Better airflow, lower cooling demand, improved circulation
Urban Layout	Courtyards, atriums, light-wells, maintain sky view	Less solar gain, avoids heat trapping, supports cooling

Our findings align with planning research showing the value of nature-based solutions. Krishnamoorthy, Mohd Adnan, and Md Yassin (2024) found that pocket parks and green corridors improve microclimate and pedestrian comfort in dense areas, supporting our evidence on vegetation and water bodies.

Likewise, Nizarudin and Zakariya (2025) stress retrofitting green infrastructure to strengthen resilience and address policy gaps, echoing our call

for integrating green space, reflective materials, and passive design into urban planning.

CONCLUSION

This study set out to examine the relationship between urban morphology, microclimate, and the Urban Heat Island (UHI) effect in Kuala Lumpur, with three specific objectives: (i) to assess how different urban forms influence thermal comfort and air quality, (ii) to evaluate the effectiveness of passive design strategies in mitigating UHI, and (iii) to provide recommendations for climate-responsive urban planning. Field measurements across Kampung Baru, Bukit Bintang, and KLCC Park demonstrated that green and water-integrated areas consistently achieved lower air temperatures and PM2.5 levels, whereas compact high-density districts experienced elevated heat loads and reduced ventilation.

The findings confirm the potential of green infrastructure, optimized building orientation, reflective materials, and passive ventilation strategies to improve both outdoor and indoor thermal comfort. Beyond design, the study highlights the need for urban policy frameworks—including the integration of the Green Building Index (GBI) and microclimate-sensitive zoning regulations—to guide sustainable development in tropical cities.

Looking ahead, future implementation pathways should focus on mainstreaming passive design at the master planning scale, enhancing tree canopy networks in pedestrian corridors, and mandating climate-responsive building codes. Further research involving long-term monitoring, seasonal data, and simulation modeling is essential to refine strategies and strengthen the evidence base for policy and practice. Ultimately, addressing UHI through integrated design and planning can significantly enhance urban livability, environmental resilience, and public health in Kuala Lumpur.

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