Dheshan, K. and Perera, N., 2026. Microclimate-driven spatial patterns for adaptive urban design: Evidence from Kotahena, Sri Lanka. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 1195 -1207. DOI: https://doi.org/10.31705/WCS.2026.87. Available from: https://ciobwcs.com/papers/

MICROCLIMATE-DRIVEN SPATIAL PATTERNS FOR ADAPTIVE URBAN DESIGN: EVIDENCE FROM KOTAHENA, SRI LANKA

Dheshan Kumar[1] and Narein Perera[2]

ABSTRACT

Rapid urbanisation and unplanned vertical expansion in tropical cities have intensified environmental pressures within dense informal neighbourhoods where urban form evolves beyond formal planning control. In many global cities, including those in Sri Lanka, everyday urban environments emerge through incremental development driven by economic constraints, with buildings predominantly constructed through labour-intensive and experience-based practices rather than professionally standardized construction processes. This ad-hoc development, combined with a growing population, has produced saturated built environments that intensify microclimate stress at street level. Interventions for such contexts typically rely on conventional sustainability frameworks that prioritise technical or climate-based solutions, while insufficiently engaging with the lived spatial and social dynamics of everyday urban environments. While climate-responsive urban research frequently evaluates environmental performance, fewer studies examine how microclimatic conditions shape spatial behaviour patterns that structure everyday urban life. This paper investigates the relationship between microclimate and spatial behaviour in dense informal contexts using Kotahena, Colombo. The study integrates spatial analysis, behavioural observation and microclimatic simulation to examine how urban morphology influences thermal comfort and patterns of urban activity. Comparative analysis reveals consistent relationships between thermal conditions and spatial behaviour patterns. The research proposes a framework for microclimate-driven spatial patterns capable of informing adaptive urban design strategies for this dense tropical environment. The patterns provide practically applicable guidance for policy and planning, supporting climate-responsive urban environments while remaining compatible with informal and experience-led urban development practices.

Keywords: *Adaptive Urban design; Informal Urbanism; Spatial patterns; Urban microclimate; Urban Sustainability.*

1. INTRODUCTION

Rapid urbanisation in developing cities has intensified environmental and social pressures, particularly within dense urban areas that have expanded beyond formal planning controls (Perera, 2014). Globally, 58% of the population now lives in urban areas, a figure projected to increase significantly by 2050 (World Bank, 2023). In many

[1] Undergraduate, Department of Architecture, University of Moratuwa, Sri Lanka, dheshank.26@uom.lk
[2] Professor, Department of Architecture, University of Moratuwa, Sri Lanka, nareinperera@uom.lk

cities of the Global South, this rapid growth has occurred largely through incremental and unplanned development, producing compact and vertically expanding urban fabrics that challenge both the urban microclimate and the social and spatial dynamics that structure everyday public life. In the Sri Lankan context, urban public spaces rarely take the form of formally planned settings such as plazas or parks. Instead, everyday streets function as the primary spatial environments through which social, cultural, and economic interactions unfold. Consequently, conventional planning approaches derived from formal Western urban models often fail to respond effectively to these conditions. Sustainable urban interventions that focus solely on environmental performance frequently prove impractical in such contexts, as they require communities to adapt to externally imposed spatial frameworks rather than responding to existing patterns of urban life.

Urban environments function through interconnected social and spatial systems (Eisner, 1985), and effective interventions must therefore operate as adaptive spatial wholes rather than isolated design elements (Alexander, 2002). Recent studies on tropical urbanism further demonstrate that microclimatic conditions directly influence patterns of pedestrian movement, occupation, and public-space usage within dense urban environments (Dissanayake et al., 2021; Emmanuel, 2005). In dense and diverse urban populations, planning strategies must therefore respond to the reciprocal relationship between microclimate and spatial behaviour within the lived dynamics of the city (Hashemi et al., 2023).

However, implementing planning policies within such contexts remains challenging due to the ad-hoc and incremental nature of urban development, where much of the built environment evolves through practice-led construction processes with limited professional involvement (Lerociyan et al., 2012). Studies on informal tropical urban environments also suggest that everyday adaptive practices such as shaded occupation, edge-based gathering, and informal commercial spillovers frequently emerge in response to local environmental conditions rather than formal planning intentions (Makevita & Rajapakse, 2013) (refer Figure 1).

Figure 1: Urban microclimate - Spatial behaviour relationship (Source: Author)

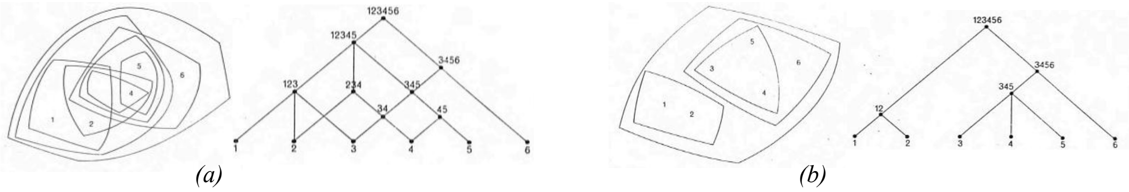
This study therefore investigates how microclimatic variation influences spatial behaviour in dense informal urban contexts, where microclimatic variation structures spatial occupation patterns in informal urban systems. By translating this relationship into a pattern-based framework, the research contributes an empirically grounded understanding of adaptive urban space in tropical cities.

2. LITERATURE REVIEW

2.1 MICROCLIMATIC CONDITIONS IN INFORMAL URBAN ENVIRONMENTS

Within dense informal urban environments, microclimate plays a significant role in mediating the relationship between built morphology and human spatial behaviour. In hot-humid regions such as Sri Lanka, interactions between urban forms and atmospheric processes significantly influence thermal conditions at street level, thereby affecting patterns of movement, occupation, and social interaction. Tropical urban environments are particularly sensitive to even minor variations in built form, land cover, and human activity (Emmanuel, 2005; Jendritzky et al., 2012).

Street orientation further modifies microclimatic performance by influencing solar exposure and airflow conditions. East-west oriented streets typically receive prolonged solar radiation on facades and pavements, increasing surface temperatures and radiant heat loads. In contrast, north-south oriented streets may experience more consistent shading but can also suffer from reduced wind permeability, affecting convective cooling. Vegetation can mitigate these conditions through shading and evapotranspiration, contributing to improved thermal comfort within urban environments.



(a) (b)

Figure 2: (a) Tree formation (b) Semi-lattice formation (Source: Alexander, 1965)

As these processes intensify within compact neighbourhoods, modifications to airflow, solar access, and surface heat storage contribute to the Urban Heat Island (UHI) effect, amplifying thermal stress within dense urban areas (Perera, 2014). The UHI phenomenon describes the tendency of urban environments to remain warmer than surrounding rural areas, particularly during night-time, and is often visualised as a dome of warmer air above built-up regions (Emmanuel, 1993).

Considering these aspects, several environmental variables become critical in defining microclimate-spatial relationships within dense urban fabrics. Key parameters include air temperature, Mean Radiant Temperature (MRT), relative humidity, wind speed and direction, and solar exposure and shading conditions. Understanding how these variables interact with urban morphology is essential for interpreting how thermal environments influence patterns of spatial occupation and behaviour within informal contexts.

2.2 MICROCLIMATE INFLUENCES ON SPATIAL PATTERNS

Within dense informal urban environments, microclimate plays a significant role in mediating the relationship between built morphology and human spatial behaviour. In hot-humid regions such as Sri Lanka, interactions between urban forms and atmospheric processes significantly influence thermal conditions at street level, thereby affecting patterns of movement, occupation, and social interaction. Tropical urban environments are particularly sensitive to even minor variations in built form, land cover, and human activity (Emmanuel, 2005).

One of the most influential spatial conditions shaping urban microclimate is the formation of urban canyons, created by closely spaced buildings along narrow streets. High Height-to-Width (H/W) ratios reduce sky view factor, limit nocturnal radiant cooling, and increase the trapping of both short-wave and long-wave radiation within street corridors. These processes generate spatially differentiated thermal environments, where certain street segments experience significantly higher radiant temperatures than others. Such variations frequently influence spatial occupation patterns, as pedestrians gravitate toward shaded and ventilated areas while avoiding thermally stressful zones. Empirical studies conducted within tropical street canyons further demonstrate that variations in MRT, airflow, and shading conditions significantly affect pedestrian comfort and duration of occupation within public spaces (Ali-Toudert, 2005; Dissanayake et al., 2021). Street orientation further modifies microclimatic performance by influencing solar exposure and airflow conditions. East-west oriented streets typically receive prolonged solar radiation on facades and pavements, increasing surface temperatures and radiant heat loads. In contrast, north-south oriented streets may experience more consistent shading but can also suffer from reduced wind permeability, affecting convective cooling.

Vegetation can mitigate these conditions through shading and evapotranspiration, contributing to improved thermal comfort within urban environments. As these processes intensify within compact neighbourhoods, modifications to airflow, solar access, and surface heat storage contribute to the Urban Heat Island (UHI) effect, amplifying thermal stress within dense urban areas (Perera, 2014). The UHI phenomenon describes the tendency of urban environments to remain warmer than surrounding rural areas, particularly during night-time, and is often visualised as a dome of warmer air above built-up regions (Emmanuel, 1993).

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2.3 RESEARCH GAP: MICROCLIMATE-SPATIAL RELATIONSHIP IN INFORMAL CONTEXTS

Although studies on urban microclimate and urban spatial behaviour are well established, they are largely examined as separate analytical domains. Limited research investigates how microclimatic conditions influence the emergence of spatial patterns within dense informal urban environments, particularly in tropical cities of the Global South where everyday streets function as primary public spaces. Existing climate-responsive urban research frequently prioritises environmental performance evaluation, while comparatively fewer empirical studies examine how measurable microclimatic variation shapes recurring behavioural occupation patterns within informal urban contexts. In tropical cities where everyday streets function as primary public spaces, understanding this relationship becomes critical for developing climate-responsive and socially adaptive urban design strategies. This study addresses this gap by empirically demonstrating how thermal variation structures spatial occupation patterns in informal urban systems and translating these relationships into a spatial pattern framework.

3. METHOD

3.1 INTRODUCTION TO CASE STUDY

Kotahena is a dense, mixed-use suburb in the northern quadrant of Colombo that has evolved largely through incremental and spontaneous urban growth. Strategically positioned between Pettah and Modara, it functions as a transitional urban zone linking the central business district with the northern residential suburbs of Colombo. With approximately 60,000 residents within an area of 2.5 km², Kotahena represents one of the most densely populated urban districts in the city. The area contains active commercial streets embedded within compact residential neighborhoods, supporting a diverse multi-ethnic urban population. Its compact urban morphology, narrow street canyons, and high building density generate distinct microclimatic conditions at pedestrian level, which directly influence patterns of spatial use, movement, and social interaction.

In addition, the area demonstrates highly adaptive informal spatial practices, where commercial spillovers, temporary shading conditions, and edge-based activities continuously reshape the use of public space. These characteristics make Kotahena a representative case for examining the relationship between urban microclimate and spatial behaviour in dense informal urban contexts.

3.2 RESEARCH DESIGN FRAMEWORK

Figure 3 illustrates the overall research design framework adopted in the study. The study adopts a mixed-method research approach combining spatial analysis, theoretical pattern comparison, empirical field observation, and microclimate simulation to examine how urban morphology, microclimate, and spatial behaviour interact within dense informal environments.

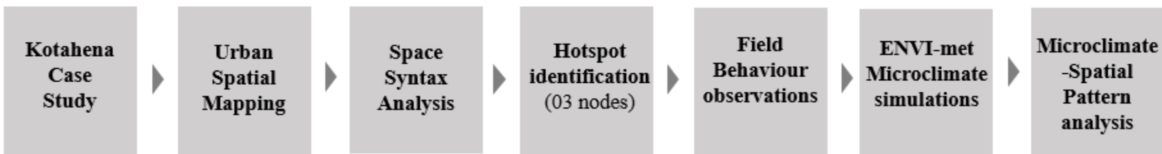


Figure 3: Research design framework (Source: Author)

The broader spatial structure of Kotahena was mapped to examine urban morphology, circulation hierarchy, and functional distribution. Spatial mapping identified commercial corridors, pedestrian movement intensities, transitional edges, and concentrations of informal occupation. Space syntax analysis identified movement networks based on spatial accessibility and visibility relationships, while connectivity analyses assessed spatial integration and potential movement concentration. Although space syntax does not directly represent human behaviour, it provided an objective framework for locating areas with a high probability of pedestrian interaction and activity concentration.

Based on spatial integration, land-use intensity, pedestrian concentration, and environmental variation, three urban hotspots were selected for detailed study. These represented distinct spatial and microclimatic conditions, enabling comparative analysis of behavioural responses across varying environments.

To establish a comparative baseline, selected spatial patterns from *A Pattern Language* (Alexander et al., 1977) were mapped against the hotspots. These patterns were chosen for their relevance to pedestrian occupation, edge conditions, activity clustering, transitional space, and climatic responsiveness in dense urban contexts. The comparison was not to validate applicability, but to examine limitations of normative planning assumptions against the spatial realities of informal tropical urbanism, enabling a structured contrast between prescribed spatial logic and emergent adaptive spatial behaviour in Kotahena. To capture real-world patterns of spatial occupation, systematic behavioural observations were conducted within the identified hotspots at strategically selected periods of the day corresponding to varying thermal conditions and activity intensities. Field observations focused on pedestrian movement patterns, stationary occupation, gathering behaviour, informal commercial spillovers, shaded occupation zones, and edge-based activities. Behavioural mapping and photographic documentation were used to capture recurring spatial occupation patterns and user responses to environmental conditions (refer Figure 4, 5 and 6).

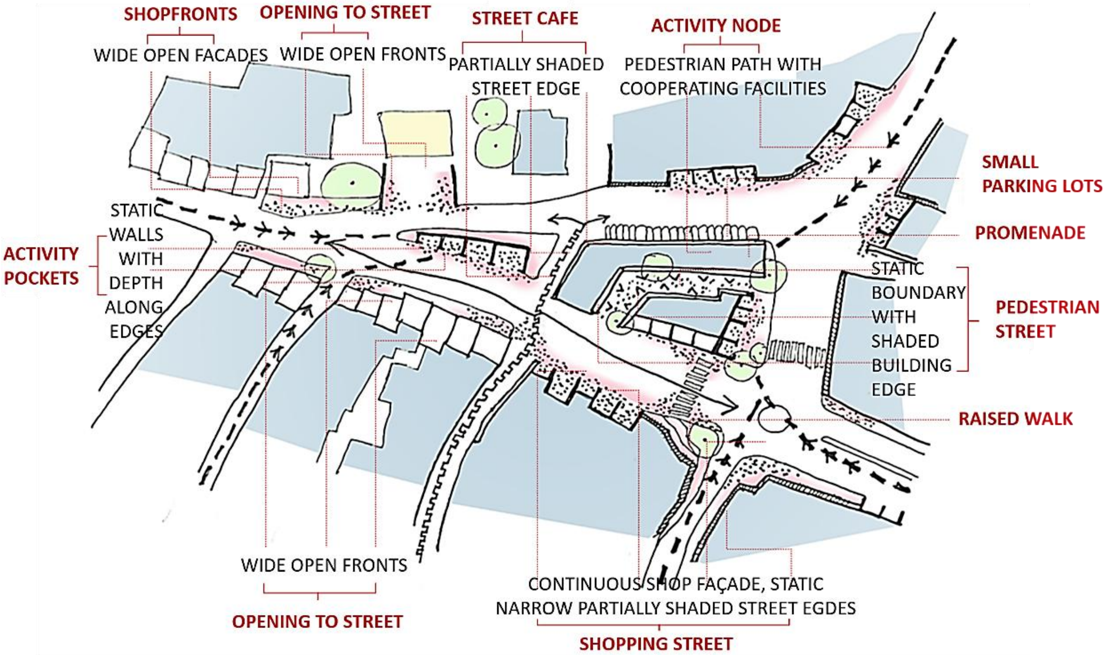


Figure 4: Theoretical pattern mapping of Hotspot 01 (Source: Author)

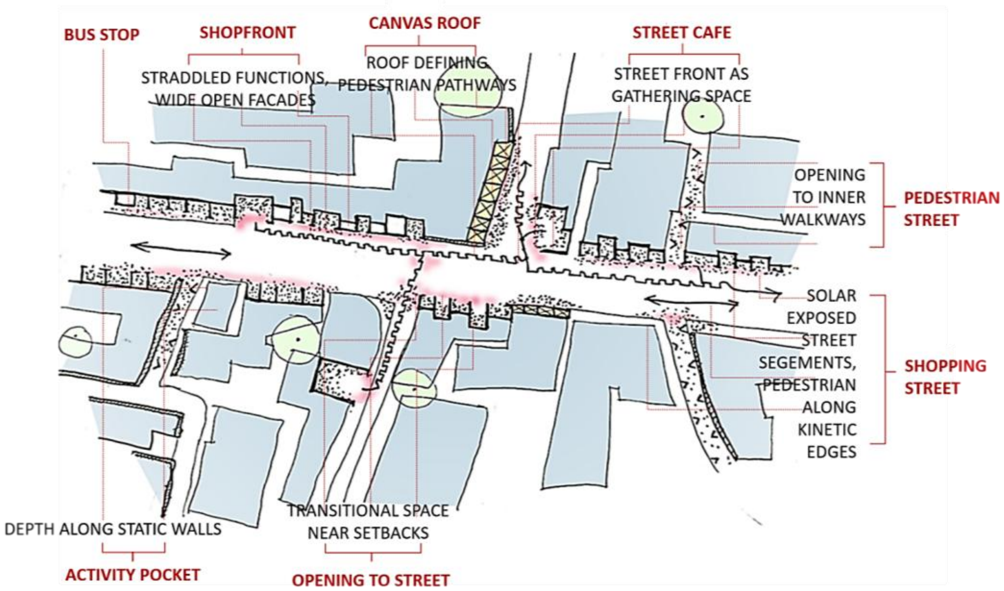


Figure 5: Theoretical pattern mapping of Hotspot 02 (Source: Author)

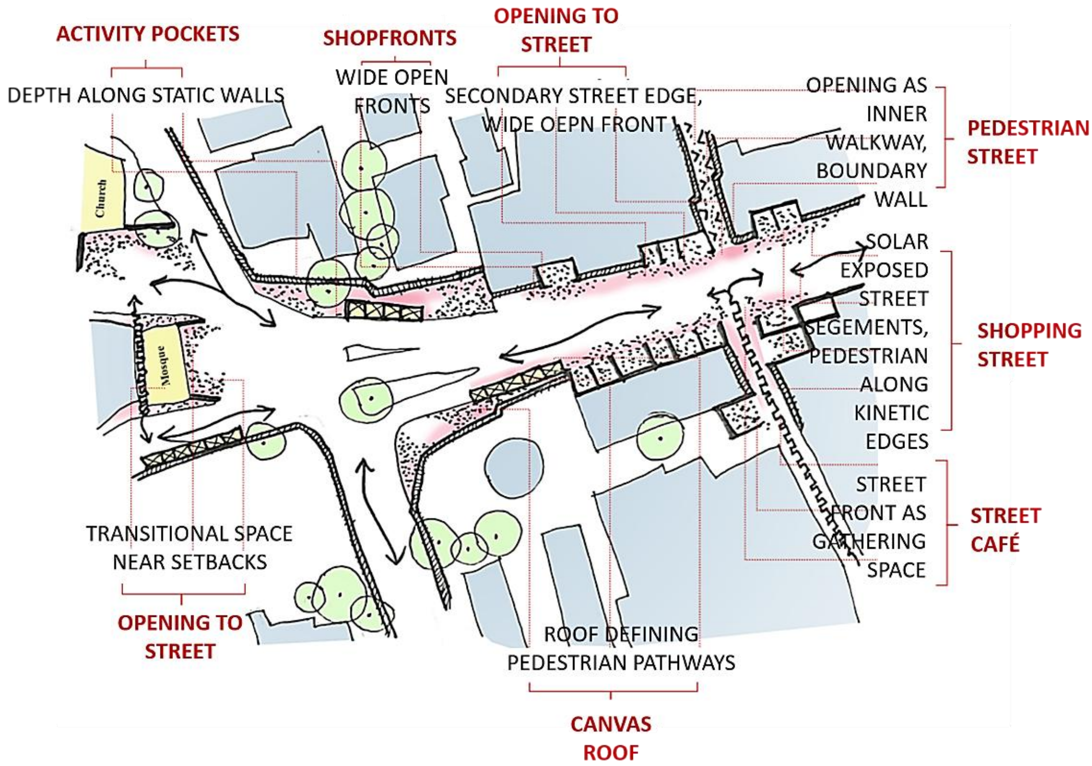


Figure 6: Theoretical pattern mapping of Hotspot 03 (Source: Author)

The same locations were subsequently modelled using the ENVI-met simulation platform to analyses key pedestrian-level microclimatic variables including Air Temperature, Relative Humidity, Wind Flow, MRT, and Predicted Mean Vote (PMV).

3.3 Simulation Protocol

Simulation models were developed to represent the existing urban morphology of the selected hotspot areas. The models incorporated street geometry, built form configuration, surface materials, and vegetation distribution in order to evaluate their influence on local microclimatic performance. Climatic input data were derived from meteorological records and validated through on-site field measurements to ensure contextual accuracy (refer Figure 7).

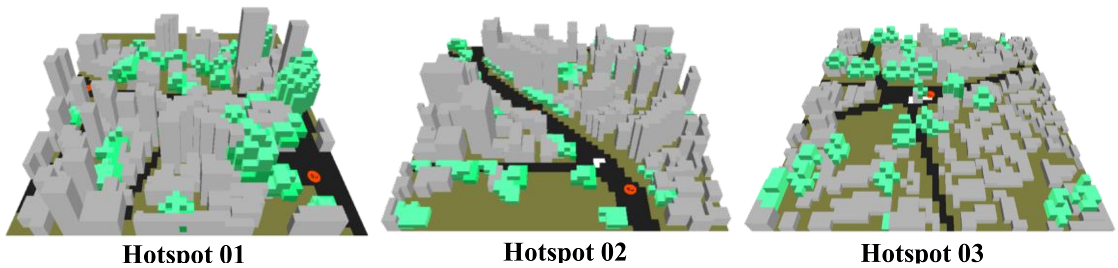


Figure 7: 3D simulation models built for testing (Source: Author)

Given the focus on commercial streets and associated public activities, the analysis examined thermal conditions between 8:00 a.m. and 6:00 p.m., corresponding to peak activity periods within the study area. This time range enabled identification of changing thermal conditions and associated behavioural responses throughout the day. The simulation models incorporated built forms, street geometry, surface materials, and vegetation patterns to evaluate how these spatial parameters influence local microclimatic conditions and associated patterns of spatial occupation. The resulting MRT and PMV outputs were comparatively analysed with observed behavioural patterns to identify recurring relationships between thermal comfort conditions and adaptive spatial use within the selected urban hotspots.

4. RESULTS AND ANALYSIS

4.1 SPATIAL MORPHOLOGY AND MICROCLIMATIC-BEHAVIORAL RESPONSE

Behavioural patterns observed across all hotspots demonstrated consistent adaptive responses to microclimatic variation (refer Table 01).

Table 01: Microclimate influence on Spatial patterns and Behavioural response

Hotspot	Spatial pattern Condition	Microclimatic condition	Behavioural Response
Hotspot 01	Narrow street canyon	MRT: 42.71°C PMV: 2.35 (midday peak thermal stress).	Reduced stationary activities and shorter pedestrian dwell times.
	Partially shaded street edge	MRT: 23.68°C–36.91°C PMV: moderate range (intermittent exposure conditions).	Short pauses and moderate pedestrian presence.
	Shaded building edge	MRT: 20.01°C–25.22°C PMV: 0.67–1.28 (reduced thermal stress).	Higher social interaction and prolonged occupation.
Hotspot 02	Solar-exposed street segment	MRT: 27.90°C–33.71°C PMV: elevated (daytime exposure conditions).	Lower pedestrian occupation and predominantly transient movement.
	Transitional space near setbacks	MRT: reduced relative to exposed segments (moderated conditions) PMV: lower than exposed zones.	Movement corridor with occasional gathering.
	Ventilated junctions	MRT: lower relative thermal load PMV: 0.97–1.24 (improved comfort during evening periods).	Higher pedestrian concentration and informal interaction.
Hotspot 03	Dense canyon corridor	MRT: elevated (restricted sky exposure condition) PMV: up to 2.19 (midday peak stress).	Limited pedestrian activity and reduced stationary occupation.
	Moderately shaded street section	MRT: 22.19°C–33.63°C PMV: moderate range	Continuous pedestrian movement and moderate occupation.
	Semi-open edge condition	MRT: lower thermal stress condition PMV: reduced during evening periods	Informal social interaction and prolonged spatial use.

(Source: Author)

Spatial environments characterised by elevated MRT and PMV values, particularly within exposed canyon segments, predominantly supported transient pedestrian movement with limited stationary occupation during peak daytime conditions. In contrast, spaces incorporating shading, setbacks, porous edges, and improved airflow consistently exhibited higher pedestrian retention, prolonged occupation, and increased informal social interaction.

4.2 MICROCLIMATE-DRIVEN BEHAVIOURAL PATTERNS AND SPATIAL ADAPTATION

Behavioural patterns observed across all hotspots demonstrated consistent adaptive responses to microclimatic variation. Spatial environments characterised by elevated MRT and PMV values, particularly within exposed canyon segments, predominantly supported transient pedestrian movement with limited stationary occupation during peak daytime conditions. In contrast, spaces incorporating shading, setbacks, porous edges, and improved airflow consistently exhibited higher pedestrian retention, prolonged occupation, and increased informal social interaction.

Temporal variation further reinforced these behavioural shifts. During midday periods, exposed street segments demonstrated minimal stationary activity, whereas shaded transitional spaces maintained moderate pedestrian presence. As thermal stress declined during evening periods, pedestrian density and duration of occupation increased across all hotspots, indicating that behavioural occupancy within dense informal urban environments is dynamically adjusted in response to measurable thermal variation.

The integrated analysis of spatial morphology, microclimate, and behavioural mapping demonstrates that microclimate acts as a spatial sorting mechanism for pedestrian behaviour across the study area. Conditions characterised by excessive enclosure, restricted airflow, and high radiant heat accumulation consistently corresponded with reduced spatial usability. Conversely, configurations incorporating ventilation corridors, spatial porosity, and transitional setbacks demonstrated improved microclimatic performance and increased pedestrian activity.

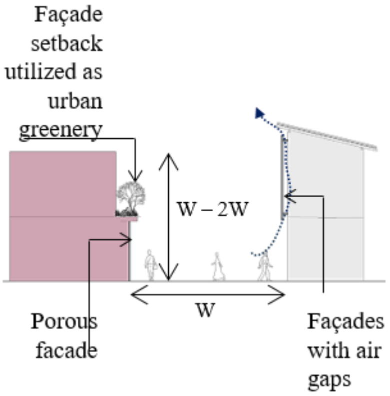
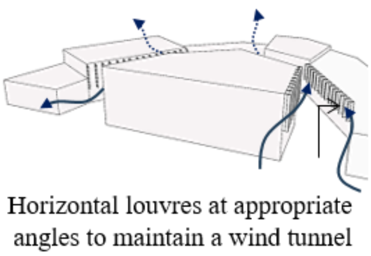
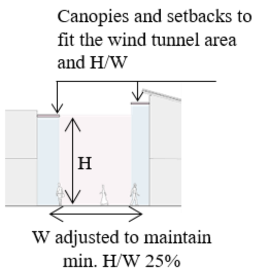
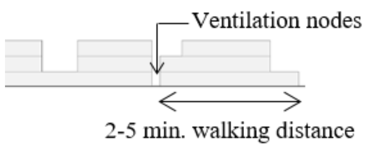
Across all hotspots, these relationships remained consistent, confirming a stable linkage between urban morphology, environmental performance, and everyday spatial use. The findings indicate that street geometry, building form, solar exposure, and ventilation operate as primary determinants of thermal comfort and behavioural distribution within dense informal urban environments. Accordingly, the combined MRT/PMV and behavioural evidence establishes a basis for defining microclimate-responsive spatial configurations capable of supporting pedestrian comfort, prolonged occupation, and adaptive social activity in tropical urban contexts.

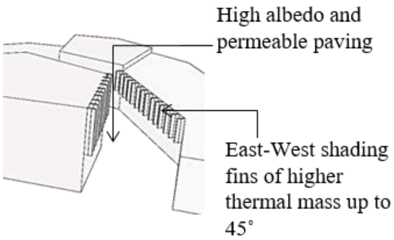
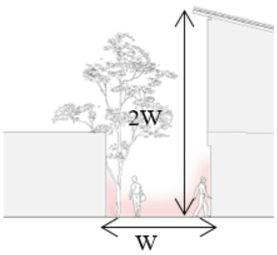
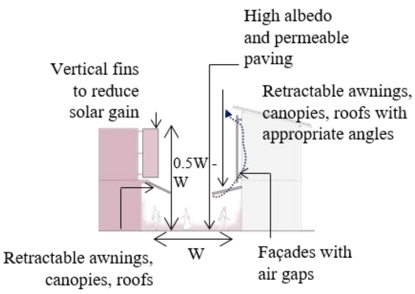
5. DISCUSSION AND CONCLUSION

5.1 PRACTICAL APPLICATION

The identified spatial patterns emerge from a consistent empirical relationship between microclimatic variation and behavioural adaptation observed across all hotspots (Refer Table 02).

Table 02: Microclimate-driven spatial patterns

Spatial Pattern	Microclimate Effect	Adaptive Spatial Strategy
Activity Nodes in Open Squares 	Heat accumulation along continuous edges. Reduced cross-ventilation. (Higher MRT and PMV peaks observed in exposed segments).	Break façades with stepped/segmented edges maintaining H/W ≈ 0.5–2.0. Introduce porous ground edges and shaded transition zones to reduce radiant heat accumulation and increase airflow permeability.
Activity Nodes along Winding Paths 	Air stagnation and uneven wind acceleration creating localized thermal variability.	Introduce façade breaks and setbacks. Use vertical fins or articulated edges. Establish ventilation nodes aligned with airflow corridors to moderate microclimatic discontinuities.
Promenades 	High solar exposure along continuous linear corridors with elevated MRT during midday.	Segment corridors with shaded pockets maintaining H/W ≤ 1. Introduce resting nodes and adjustable shading systems (0–45°) to reduce thermal exposure and support pedestrian retention.
Shopping Streets 	Urban canyon heat build-up with restricted ventilation and high PMV values in peak hours.	Introduce cross passages. Break continuous façades with setbacks. Apply ventilated cladding or shading fins.

Spatial Pattern	Microclimate Effect	Adaptive Spatial Strategy
Shopfront Edges 	Localised heat accumulation at thresholds due to direct solar exposure.	Use recessed entrances, angled façades to enhance airflow deflection, and combine permeable paving with shading fins to reduce thermal stress at pedestrian interfaces.
Openings to Communal Life 	Improved ventilation and reduced MRT in cross-connected spatial zones. Heat retention along enclosed public edges with limited air exchange.	Introduce courtyard gaps, maintain visual permeability, and orient openings toward prevailing wind directions to enhance cooling efficiency and social activation.
Edges of Activity Pockets 	Heat retention along enclosed public edges with limited air exchange.	Maintain porous lower edges, introduce stepped façade articulation, and integrate vertical shading systems that facilitate upward heat dissipation.

(Source: Author)

Rather than being abstract design propositions, these patterns represent performance-based spatial responses to thermal stress in dense informal urban environments. Importantly, the identified patterns are not abstract design propositions; they are directly derived from consistent empirical correspondences between measured microclimatic variations (MRT and PMV outputs) and observed behavioural adaptations across the three analysed hotspots.

The identified patterns demonstrate consistent alignment between measured microclimatic performance and observed spatial behaviour across all three hotspots. Across the dataset, zones exhibiting lower MRT and PMV values consistently corresponded with increased pedestrian retention, prolonged occupation, and higher levels of informal social interaction. Conversely, thermally stressed zones with elevated MRT values consistently functioned as transient movement corridors with limited stationary activity.

This systematic correspondence establishes that spatial behaviour in dense informal urban environments is strongly conditioned by measurable microclimatic variation mediated through urban morphology. Accordingly, the proposed spatial patterns are derived through a triangulated evidence framework combining: Spatial morphology analysis, ENVI-met derived microclimatic simulation outputs and Behavioural observation mapping. This triangulation strengthens the validity of the transition from analytical findings to design implications, ensuring that the proposed patterns are evidence-based rather than interpretative constructs.

The practical relevance of these patterns lies in their applicability to sustainable urban design and incremental upgrading strategies in dense tropical cities. They can inform design decisions related to building setbacks, façade articulation, shading strategies, ventilation corridors, and public space configuration. Unlike conventional form-driven design approaches, the proposed framework links urban morphology directly to pedestrian thermal experience and spatial behaviour. This enables a performance-based understanding of informal urban space, where design interventions can be aligned with microclimatic regulation and everyday spatial practices to improve comfort, usability, and social activity in tropical cities.

5.2 FURTHER RESEARCH

This study identifies a set of microclimate-driven spatial patterns grounded in the local context of Kotahena, demonstrating how spatial form, movement networks, and everyday urban practices shape thermal comfort and public life. As the findings are based on a limited number of hotspots, future research should extend this approach to larger urban areas, diverse land-use typologies, and multiple climatic zones.

Future studies should incorporate higher-resolution behavioural datasets, extended seasonal monitoring, and multi-temporal simulations to capture long-term variations in microclimate-behaviour relationships. Longitudinal and comparative multi-site studies would strengthen the transferability and predictive capacity of the proposed framework. Further development may also integrate advanced simulation tools, machine learning approaches, and real-time environmental sensing to enhance adaptive urban performance modelling.

5.3 CONTRIBUTIONS

This research reframes informal urban environments as sites of adaptive climatic intelligence rather than planning deficiency. By integrating microclimatic analysis with spatial and behavioural dynamics, the study challenges conventional sustainability approaches that prioritise environmental performance in isolation from lived urban experience.

The key contribution of this study lies in establishing a direct empirical linkage between microclimate (MRT/PMV) variation and observable spatial behaviour and translating this relationship into a structured set of adaptive spatial design patterns. It advances a human-centred, pattern-based design framework that aligns climatic responsiveness with everyday spatial practices. In doing so, the study provides urban designers, planners, and policymakers with a transferable evidence-based methodology for developing resilient, inclusive, and climatically adaptive urban environments in rapidly transforming tropical cities.

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