URBAN BLUE-GREEN INFRASTRUCTURE FOR CLIMATE RESILIENCE: INTEGRATING THERMAL COMFORT IN SRI LANKAN PUBLIC SPACES

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Abstract: This study investigates how urban blue-green infrastructure (BGI), urban systems combining vegetation and water-based elements to enhance ecological performance and thermal comfort. Under ASHRAE Standard 169, Jaffna falls within Climate Zone 0A (Extremely Hot and Humid), making thermal comfort enhancement essential for sustainable urban living. Two key sites, Aariyakulam Lake Trail and Pannai Coastal Promenade, were analysed using empirical field measurements, user surveys, and ENVI-met simulations. Thermal comfort was evaluated through the Predicted Mean Vote (PMV) and Thermal Sensation Vote (TSV) models, supported by on-site climatic data.

Results show that BGI significantly reduces urban heat stress, with the Pannai Coastal Park registering lower PMV and higher Thermal Comfort Vote (TCV) values than Aariyakulam Lake Trail due to its greater vegetation density, coastal proximity, and improved airflow. Users consistently preferred shaded areas, trees, water features, and breezy zones, while prolonged stays correlated strongly with thermally comfortable microclimates, confirming the relationship between design and inclusive social interaction. Empirical and simulated data validate the measurable cooling effects of BGI, demonstrating its effectiveness as a climate adaptation strategy in tropical warm-dry environments. The study develops a contextual framework linking thermal comfort and climate resilience, offering policy recommendations for biodiversity-positive urban design and public space planning in Sri Lanka's evolving coastal cities.

Keywords:*Thermal Comfort, Blue-Green Infrastructure, Urban Resilience, Public Spaces, Climate-Responsive Design*

1. Introduction

Rising temperatures and rapid urbanization are increasingly challenging the liveability of tropical cities. The Urban Heat Island (UHI) effect caused by dense construction, limited vegetation, and heat-retaining materials has intensified heat stress in Sri Lanka's urban environments (Emmanuel, 2005; Simath & Emmanuel, 2022). Jaffna, one of the country's fastest-developing coastal cities, is particularly vulnerable due to its compact urban form, minimal shade provision, and high exposure to solar radiation. Short-term cooling strategies, such as street water spraying, offer temporary relief but fail to address the deeper climatic imbalance created by the city's built environment.

In this context, Blue-Green Infrastructure (BGI) has emerged as a vital component of climate-responsive urban design. BGI refers to urban systems that combine vegetation and water-based elements such as lakes, wetlands, tree canopies, and waterfronts to enhance ecological performance, thermal comfort, and social well-being (Norton et al., 2015; Qiu et al., 2023). Through processes such as shading, evapotranspiration, and wind regulation, these systems moderate urban microclimates while simultaneously supporting biodiversity and recreation. For cities like Jaffna, located in ASHRAE Climate Zone 0A (Extremely Hot and Humid), such interventions are crucial to maintaining outdoor comfort and resilience. Current measures by municipal authorities, like water spraying on streets to cool them, offer only temporary relief, highlighting the need for more sustainable and long-term solutions. There is a noticeable deficit of outdoor spaces that provide thermal comfort, such as shaded green areas and designated relaxation zones within the urban core.

However, despite global progress in BGI research, empirical evidence from Sri Lanka's warm-dry coastal contexts remains scarce. Few studies have examined how the spatial configuration of blue-green networks directly influences outdoor thermal comfort. This absence of localized data limits the ability of planners and designers to implement evidence-based, climate-adaptive landscape strategies. To address this gap, this study investigates how urban blue-green infrastructure contributes to outdoor thermal comfort and inclusive use in Jaffna's public spaces through empirical field measurements, user surveys, and ENVI-met simulations. The research focuses on two representative sites Aariyakulam Lake Trail and Pannai Coastal Promenade, selected for their contrasting spatial and environmental characteristics. Thermal comfort was analysed using the PMV and TSV models, supported by site-specific climatic data.

By evaluating both microclimatic performance and user perception, this study identifies how vegetation density, water proximity, and airflow influence comfort levels and behavioural patterns. The findings aim to clarify the relationship between thermal design, offering context-sensitive insights for planners and policymakers. Ultimately, this research contributes to the growing discourse on climate-responsive urban design by situating BGI as a practical and adaptive strategy for improving outdoor resilience in Sri Lanka's evolving coastal cities.

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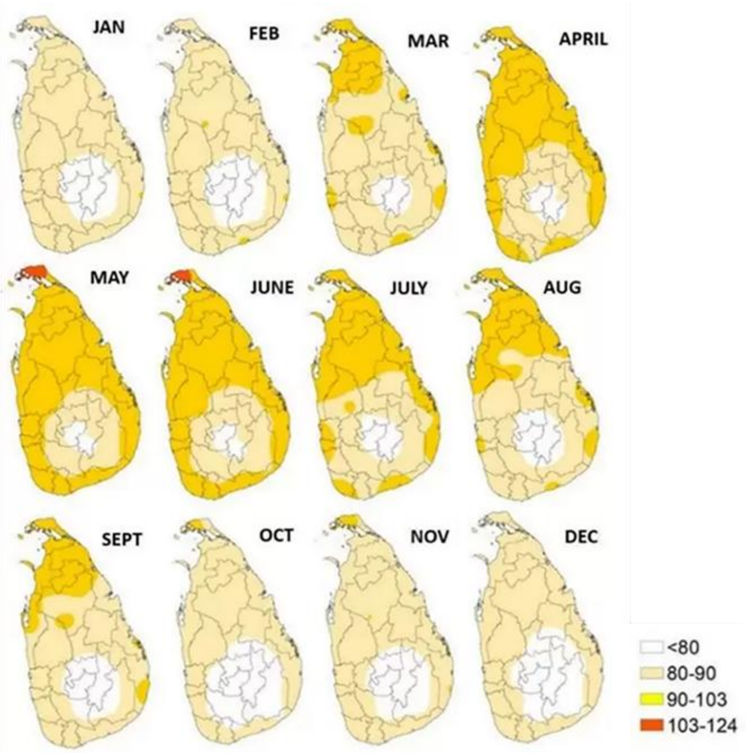

Classification	Heat Index	Effect on the body
Caution	80°F - 90°F	Fatigue possible with prolonged exposure and/or physical activity
Extreme Caution	90°F - 103°F	Heat stroke, heat cramps, or heat exhaustion possible with prolonged exposure and/or physical activity
Danger	103°F - 124°F	Heat cramps or heat exhaustion likely, and heat stroke possible with prolonged exposure and/or physical activity
Extreme Danger	125°F or higher	Heat stroke highly likely

Figure 1 Average heat index of Sri Lanka in 2019 by drought.lk

Figure 2 Image of main street Jaffna on a hottest month by sundaytimes.lk

2. Literature Review and Theoretical Framework

2.1 GLOBAL PERSPECTIVES ON BLUE-GREEN INFRASTRUCTURE AND URBAN RESILIENCE

Rapid urbanization and the proliferation of impervious surfaces have intensified the Urban Heat Island (UHI) effect, where built-up areas record higher temperatures than their rural surroundings. This thermal imbalance, driven by the concentration of buildings, paved surfaces, and anthropogenic heat emissions, contributes to heat stress a physiological strain that impairs human comfort and health in hot climates (De Abreu-Harbich et al., 2015). Blue–Green Infrastructure (BGI), the deliberate integration of vegetated and aquatic systems such as parks, wetlands, rivers, lakes, and urban forests, has emerged globally as a key nature-based solution for moderating urban microclimates and enhancing environmental resilience (Norton et al., 2015; Qiu et al., 2023). The World Health Organization (WHO) and UN-Habitat emphasize BGI's dual ecological and social functions: cooling the environment through shading, evapotranspiration, and radiation reflection, while simultaneously supporting recreation, mental well-being, and community cohesion (Peng et al., 2016; Yu et al., 2020). Research consistently shows that BGI's cooling performance is influenced by vegetation type, canopy density, hydrological features, and spatial configuration. Denser vegetation and connected blue-green networks enhance wind circulation, reduce surface temperatures, and improve human thermal comfort (Xiao et al., 2022) Global case studies demonstrate that multi-layered planting, permeable surfaces, and water features can reduce surface temperatures by 2–5 °C, providing measurable relief from heat stress (Taleghani et al., 2015). Increasingly, urban planners employ remote sensing data and microclimatic simulations to quantify these effects, optimizing landscape design to balance ecological, climatic, and social outcomes (Gunawardena et al., 2017).

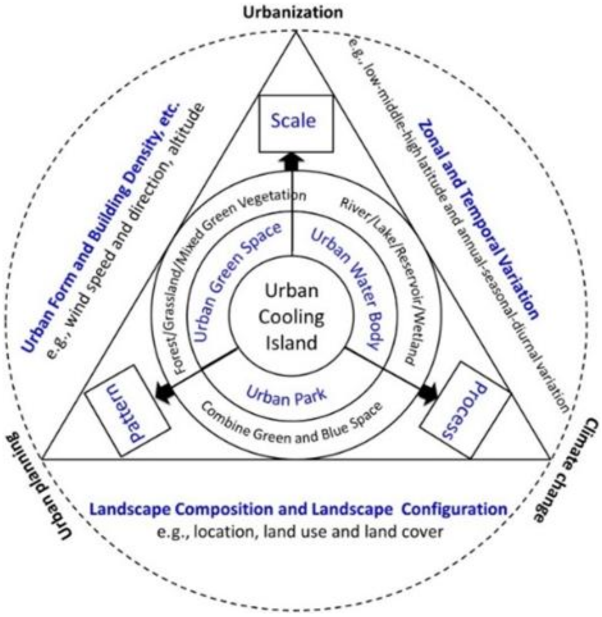

Figure 3 Cooling effect of urban blue-green space and threshold-size-based UHI mitigation studies
Source: Yu et al ,2020

Within the South Asian context and particularly in Sri Lanka's warm-dry climatic zones, BGI plays a crucial role in urban climate adaptation. Traditional water bodies such as *kulams* (tanks) and coastal wetlands historically served as cooling and community spaces. However, modern urban expansion in Jaffna has fragmented these systems, reducing their ecological and climatic effectiveness (Simath & Emmanuel, 2022). Reintegrating and redesigning such networks are therefore central to improving thermal comfort, resilience, and liveability in Sri Lankan cities.

2.2 THERMAL COMFORT PRINCIPLES

Thermal comfort is defined as "the condition of mind that expresses satisfaction with the thermal environment" (ASHRAE 55). It represents an interplay between objective physical parameters air temperature, humidity, radiation, and wind, and subjective human factors such as metabolic rate, clothing insulation, and psychological adaptation (Fanger, 1972; Nikolopoulou & Steemers, 2003). In outdoor environments, comfort levels are typically evaluated using bioclimatic indices such as the Predicted Mean Vote PMV, Physiological Equivalent Temperature (PET), and Universal Thermal Climate Index (UTCI). The PMV model, originally developed for indoor applications (Fanger, 1972), has been extended to outdoor contexts through the Klima-Michel Model (KMM), which incorporates solar radiation, wind exposure, and humidity (Jendritzky & Nübler, 1981; Matzarakis & Mayer, 1997). Tools such as ENVI-met and RayMan simulate these complex interactions, generating spatially detailed comfort maps to guide landscape and urban design (Zhou et al., 2015; Yang et al., 2021).

Urban design morphology has a decisive influence on outdoor thermal comfort. The arrangement of buildings, street orientation, open-space distribution, and vegetation cover jointly determine how solar radiation, wind, and shade interact within the urban microclimate (Ali-Toudert & Mayer, 2006; Emmanuel & Fernando, 2007). Compact urban blocks with limited ventilation corridors tend to trap heat, intensifying the Urban Heat Island effect, whereas layouts that enable airflow and sky view support convective cooling and heat dissipation (Oke, 1988; Johansson & Emmanuel, 2006). Integrating blue-green spaces such as parks, lakes, and vegetated corridors into these built forms further reduces surface and air temperatures through evapotranspiration, shade, and radiation reflection (Bowler et al., 2010; Gunawardena et al., 2017). Studies in tropical cities demonstrate that even small design adjustments like aligning streets with prevailing wind directions or incorporating continuous tree canopies can lower perceived temperatures by 2–4 °C (Norton et al., 2015). Consequently, achieving outdoor thermal comfort is not solely a climatic or material consideration but a spatial design challenge that links urban morphology, microclimatic performance, and human experience.

Complementing these computational methods, field surveys using Thermal Sensation Votes (TSV) and Thermal Comfort Votes (TCV) capture real human experiences. Integrating measured and perceived data provides a comprehensive understanding of how people interpret and adapt to thermal environments (Lin et al., 2010; Fabbri et al., 2017). Such mixed-methods approaches are particularly valuable in tropical contexts, where local acclimatization and cultural habits shape perceptions of comfort differently from temperate regions.

2.3 CONCEPTUAL AND THEORETICAL FRAMEWORK

This study adopts an integrative framework linking ecological design, human adaptation to evaluate the performance of blue-green spaces in Jaffna. At the core is the Adaptive Thermal Comfort Theory (de Dear & Brager, 1998), which posits that comfort expectations evolve with experience, cultural background, and behavioural adjustments. People adapt to thermal environments through both physiological acclimatization (altered heat tolerance) and psychological adaptation (expectations and perceived control). In warm-dry climates, such as northern Sri Lanka, users typically demonstrate broader comfort ranges, tolerating higher operative temperatures due to long-term exposure and cultural familiarity (Lam et al., 2021). Complementary frameworks, Protection Motivation Theory (Rogers, 1975) and Self-Determination Theory (Deci & Ryan, 2000), help explain behavioural responses to environmental stress, such as seeking shade or altering activity levels. These theories inform the interpretation of field observations, revealing how landscape design influences adaptive behaviours and perceptions of comfort. This theoretical lens aligns with global resilience paradigms, including the IPCC Urban Resilience Framework and UN-Habitat's Principles for Sustainable Urban Development, which advocate nature-based, inclusive design as essential for climate adaptation. By combining biophysical factors (e.g., shading, wind movement, vegetation density, surface albedo) with social and psychological dimensions (e.g.,user experience), the framework situates thermal comfort within a broader discourse of urban resilience.

Accordingly, the Integrated Blue–Green Comfort Framework guiding this study conceptualizes Jaffna's parks as multifunctional systems that mediate between climate regulation, public well-being, and inclusive urban design. This approach provides a robust theoretical basis for assessing how landscape configuration, environmental performance, and human adaptation intersect to shape thermal comfort in tropical urban settings.

3. Research Methodology and Data Collection

3.1 RESEARCH FRAMEWORK

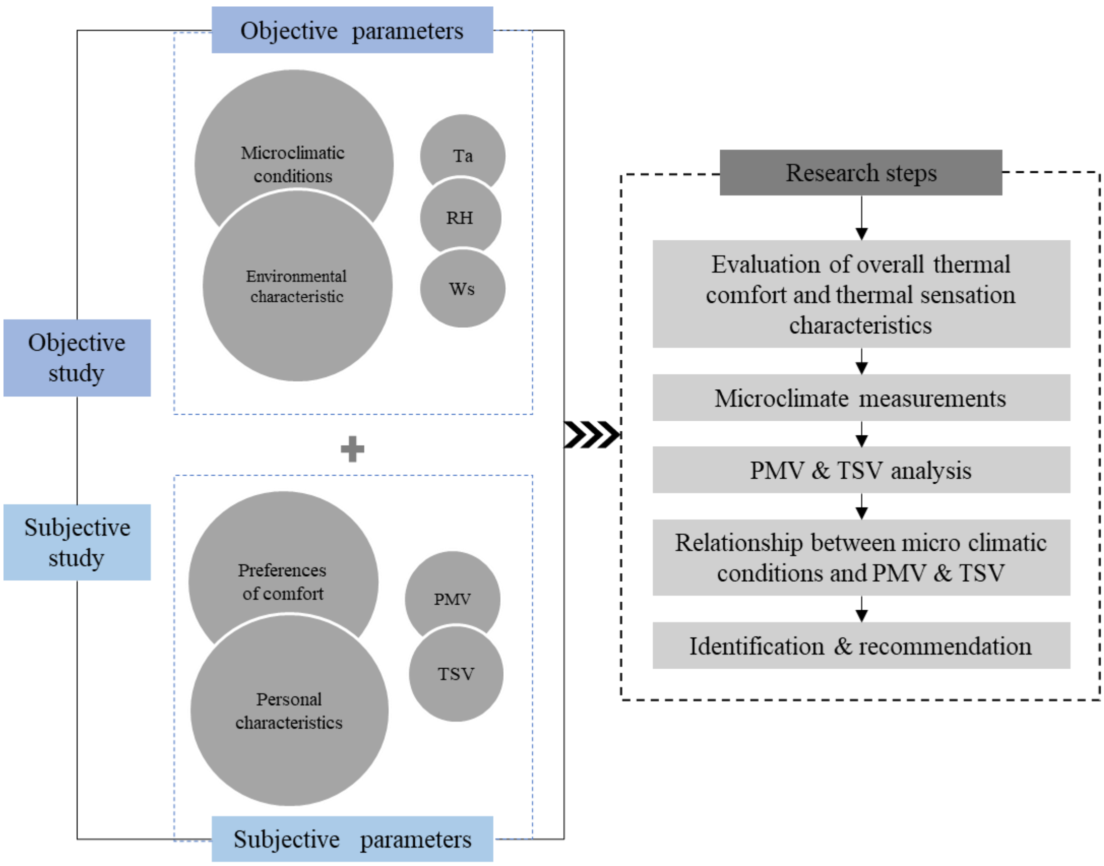

Figure 4 Research design compiled by author

A mixed-methods research design was selected to gain a comprehensive understanding of thermal comfort and blue-green space design in Jaffna. This approach combines quantitative analysis, involving meteorological measurements, with qualitative analysis through surveys and interviews for additional validation. The PMV is simulated using high-resolution microclimatic simulation software called ENVI Met. All these methods are utilized to assess the level of thermal comfort provided by the studied areas.

3.2 LOCAL CLIMATE CONTEXT

Jaffna falls within the warm, dry climatic zone according to the ASHRAE 55 standard. It experiences a tropical savanna climate, characterized by a dry season from February to August and a wet season from September to January. Jaffna has the highest average temperature in Sri Lanka, averaging around 83°F (28.3°C). The hottest periods occur in April–May and August–September, while the coolest months are December–January. The region receives most of its annual rainfall from the Northeast monsoon. This research was conducted in July, the hottest month of the year.

	January	February	March	April	May	June	July	August	September	October	November	December
Avg. Temperature °C (°F)	25.5 °C (77.8) °F	26.3 °C (79.3) °F	27.8 °C (82.1) °F	29.1 °C (84.4) °F	29.3 °C (84.8) °F	29 °C (84.2) °F	28.8 °C (83.8) °F	28.4 °C (83.2) °F	28.2 °C (82.8) °F	27.4 °C (81.3) °F	26.3 °C (79.4) °F	25.7 °C (78.3) °F
Min. Temperature °C (°F)	24.3 °C (75.7) °F	24.7 °C (76.5) °F	25.8 °C (78.5) °F	27.2 °C (81) °F	28 °C (82.4) °F	27.8 °C (82.1) °F	27.4 °C (81.4) °F	27 °C (80.7) °F	26.8 °C (80.2) °F	25.9 °C (78.6) °F	25 °C (77.1) °F	24.7 °C (76.4) °F
Max. Temperature °C (°F)	26.8 °C (80.2) °F	28.1 °C (82.5) °F	30.2 °C (86.3) °F	31.3 °C (88.4) °F	31.1 °C (88) °F	30.6 °C (87.2) °F	30.5 °C (87) °F	30.3 °C (86.5) °F	30.1 °C (86.2) °F	29 °C (84.2) °F	27.6 °C (81.8) °F	26.9 °C (80.4) °F
Precipitation / Rainfall mm (in)	69 (2)	29 (1)	26 (1)	54 (2)	64 (2)	28 (1)	35 (1)	52 (2)	70 (2)	218 (8)	318 (12)	189 (7)
Humidity(%)	75%	74%	74%	76%	78%	76%	75%	76%	77%	80%	82%	78%
Rainy days (d)	6	4	3	8	7	4	7	8	9	16	16	13
avg. Sun hours (hours)	7.2	8.2	9.1	9.6	9.9	10.6	10.7	10.3	9.7	8.6	7.5	7.2

Data: 1991 - 2021 Min. Temperature °C (°F), Max. Temperature °C (°F), Precipitation / Rainfall mm (in), Humidity, Rainy days. Data: 1999 - 2019: avg. Sun hours

Figure 5 Climate information of Jaffna by: meteo.gov.lk

3.3 STUDY LOCATIONS

Two public parks in Jaffna were selected to represent different blue-green settings.

Case Study 1 – Aariyakulam Park (9°40'5"N, 80°1'8"E):
Located near the city centre, this park includes a natural lake surrounded by trees and open lawns. It has shaded areas that attract visitors for walking, sitting, and social activities. Two shaded areas were chosen for monitoring.

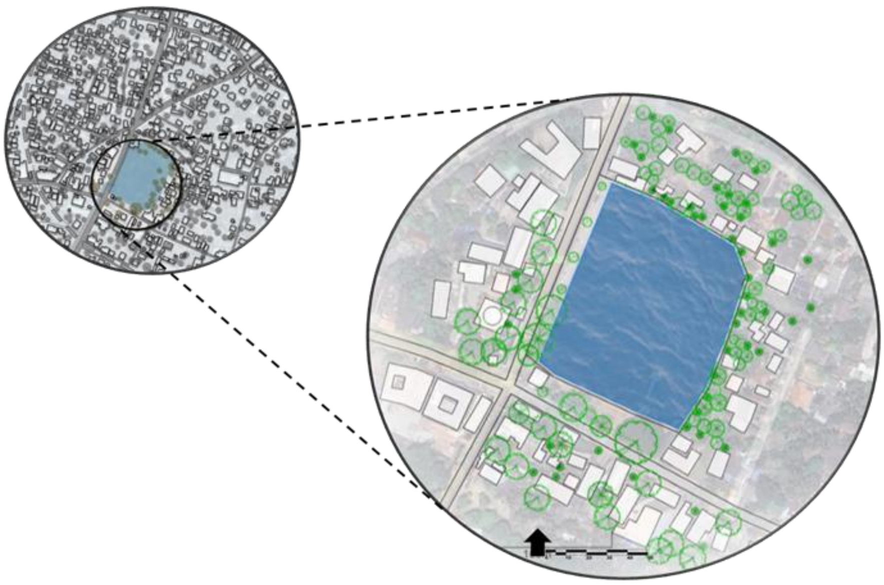

Figure 6 Aariyakulam case study area map by author

Case Study 2 – Pannai Park (9.6794°N, 80.0001°E):
This coastal park lies along the Jaffna Lagoon. It includes open lawns, seating areas, and walking trails close to the water. Two points were selected to measure both shaded and exposed conditions near the shore.

These sites represent two different urban environments, inland vegetated and coastal open, allowing comparison of how design and setting affect comfort.

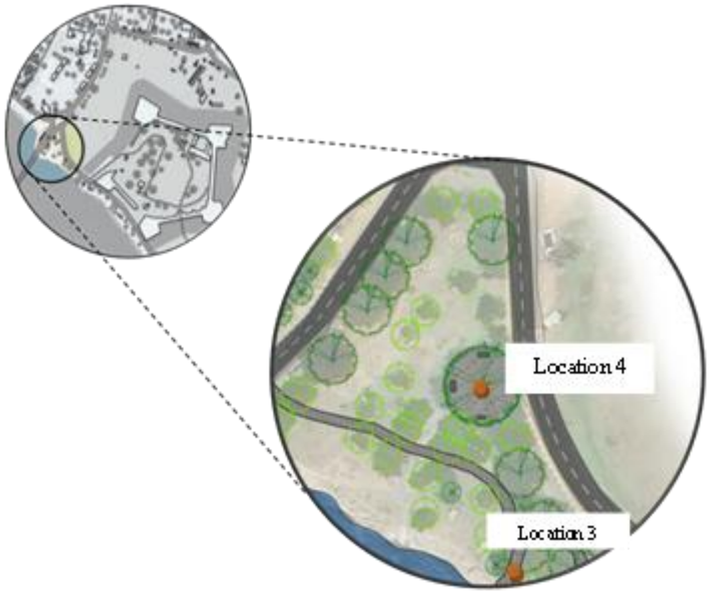

Figure 7 Pannai park case study area map by author

3.4 FIELD DATA COLLECTION AND THERMAL COMFORT ASSESSMENT

Field measurements were conducted on 12–13 August 2023 (ISO 7726), recorded every minute from 9:00 a.m. to 6:00 p.m. Air temperature and relative humidity were measured using HOBO H8 data loggers, and wind speed was measured with portable anemometers. All instruments were positioned at 1.1 m above ground in shaded areas. Thermal comfort was evaluated using the Predicted Mean Vote (PMV) model (Fanger, 1972) adapted for outdoor conditions via the Klima–Michel Model (KMM) (Matzarakis & Mayer, 1997). ENVI-met simulations produced spatial maps of comfort levels across the parks. A short survey of 60 randomly selected visitors captured thermal sensation (–3 "cold" to +3 "hot"), comfort votes, and adaptive behaviours such as seeking shade or visiting during cooler times. Of these participants, 53% were male and 47% female; 35% were aged 18–30 years, 40% were 31–50 years, and 25% were 51 years or older. Regarding occupation, 28% were students, 47% were employed, and 25% were retired or engaged in other activities.

4.Results and Discussion

4.1 MICROCLIMATIC OBSERVATIONS

Air temperature, humidity, and wind speed varied between the two parks, influencing how comfortable visitors felt. Although both Aariyakulam Park and Pannai Park recorded similar overall air temperatures, their thermal sensations differed due to shading, vegetation, and exposure. At Pannai Park, the open coastal setting allowed higher morning and midday temperatures, rising from around 31°C in the morning to about 34°C in the evening, mainly because of direct sunlight and stored surface heat. In contrast, Aariyakulam Park, shaded by a dense tree canopy, remained cooler in the evening as the vegetation reduced heat retention. Relative humidity values were generally similar across both sites, confirming that the climatic conditions during data collection were comparable. However, humidity in Pannai Park was slightly higher in the afternoon because of sea evaporation and coastal moisture, while Aariyakulam's humidity stayed steady throughout the day. Wind speed was the main differentiating factor: Pannai Park experienced stronger sea breezes that improved ventilation and comfort, especially in open areas, whereas Aariyakulam Park, surrounded by buildings and dense vegetation, had lower wind movement and more sheltered air. These observations show that shade, openness, and coastal winds play a key role in determining outdoor thermal comfort in Jaffna's blue-green spaces.

4.2 PMV ANALYSIS OF THERMAL COMFORT IN BOTH CASE STUDIES

The PMV spatial distribution map for Aariyakulam Lake Trail shows noticeable variations in thermal conditions. Areas close to the lake, including the study locations, recorded lower PMV values (1.29–3.26), indicating a *slightly warm to warm* comfort level. In contrast, the adjoining road areas displayed higher PMV values (3.75–4.25), categorized as *hot to very hot*. These differences are mainly influenced by proximity to water bodies and variations in landscape design, particularly the amount of vegetation and the type of surface materials used.

In Pannai Park, the PMV map revealed generally lower values than Aariyakulam, reflecting its coastal setting and stronger airflow. The study locations recorded PMV values between 1.6 and 2.33, representing a *slightly warm* comfort condition. Shaded areas with dense tree cover were significantly more comfortable than open zones without trees, where PMV values rose to 3.05–3.77, corresponding to *warm to hot* conditions. These findings confirm that blue-green features and coastal winds substantially improve outdoor thermal comfort.

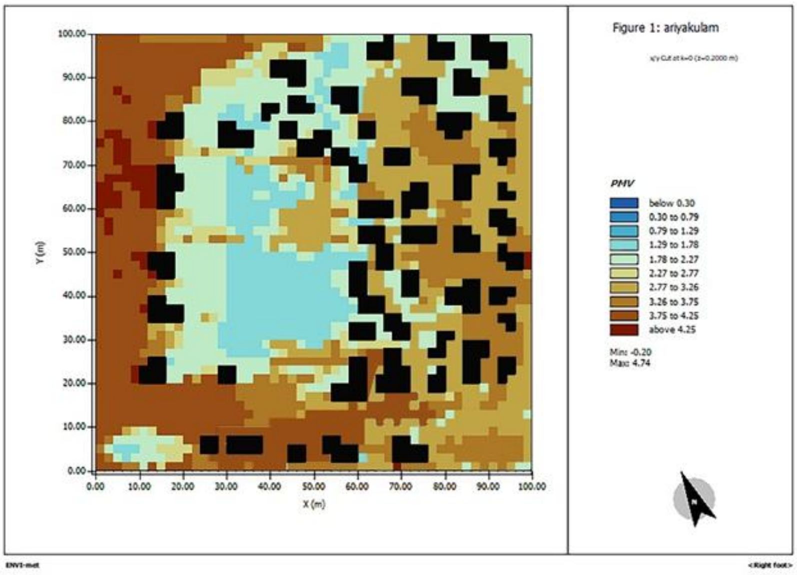

Figure 8 PMV results simulated for Aariyakulam lake area by author

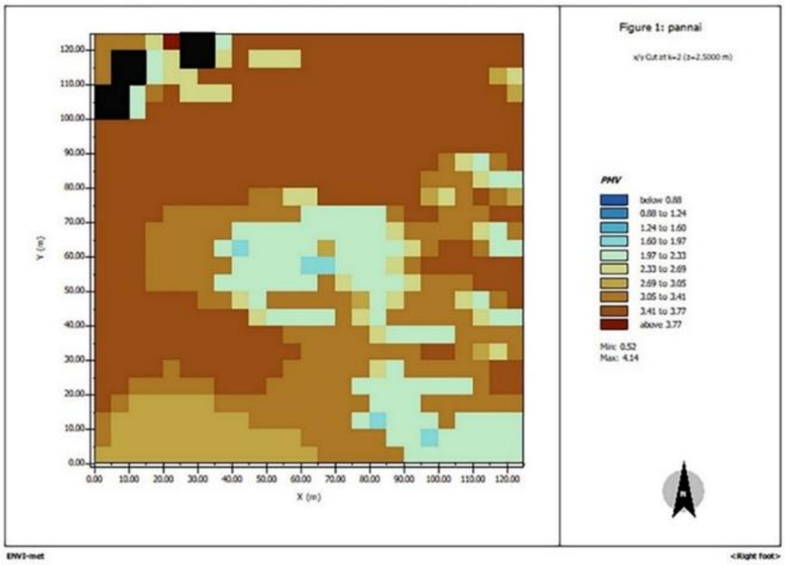

Figure 9 PMV results simulated for Pannai park area by author

4.3 TSV AND TCV ANALYSIS

Thermal Sensation Vote (TSV) and Thermal Comfort Vote (TCV) results showed that most visitors in all locations felt warm or slightly hot, though they generally rated the spaces as moderately comfortable. At Location 1 (Aariyakulam – open paved area), many participants reported discomfort due to direct sunlight and heat from surfaces, noting that limited shading increased the sensation of heat. In Location 2 (Aariyakulam – shaded under Samanea Saman trees), people felt more comfortable, as the tree canopy and soil surface helped lower heat levels. At Location 3 (Pannai Park – semi-open area), respondents perceived the space as hotter but still acceptable, suggesting that comfort was influenced by views, breeze, and activity, not only temperature. In Location 4 (Pannai Park – exposed coastal zone), participants also felt thermally hot but moderately comfortable, likely due to sea breezes and visual openness, even though shade and wind barriers were limited. Overall, the findings highlight that shade, surface material, and wind movement strongly influence people's perceived and actual comfort in Jaffna's blue-green public spaces.

4.4 PREFERRED LANDSCAPE ELEMENTS INFLUENCING THERMAL COMFORT CHOICES

Survey responses showed clear preferences for natural and shaded environments that reduce exposure to direct sunlight. Trees, plants, and shaded structures were the most valued elements, as they provided cooler and more comfortable areas for rest and social activity. Water features, such as ponds and fountains, were also highly appreciated because they lowered nearby air temperatures through evaporative cooling. Many visitors preferred areas with gentle breezes for natural ventilation, noting that these spots felt more pleasant even at higher temperatures. In contrast, hard paved areas and concrete seating were often described as uncomfortable during hot hours, as they absorbed and radiated heat. These findings indicate that combining vegetation, water, and airflow creates a more comfortable and inclusive outdoor environment. Integrating such features into urban design can enhance both thermal comfort and social well-being.

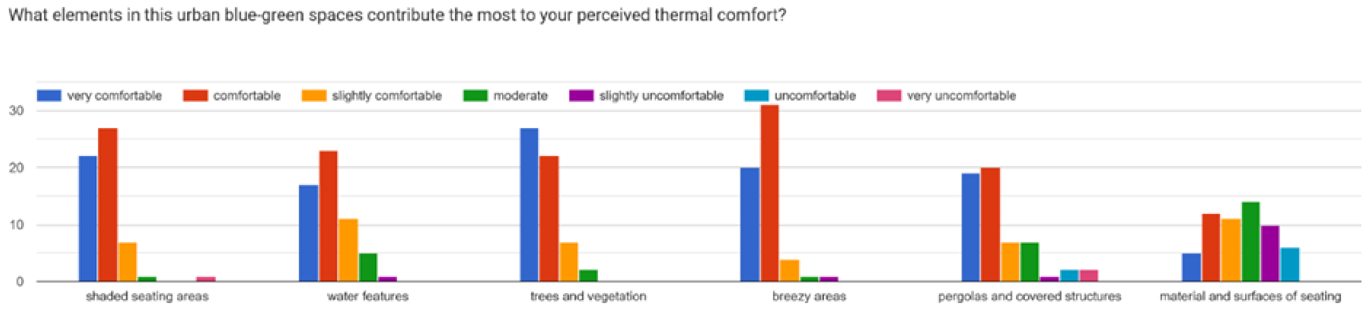

Figure 10 User Time Spent and Preferences at Study Locations Based on survey results by the author

5. Conclusion

The study found that thermal comfort in Jaffna's urban blue–green spaces is shaped by both environmental conditions and human adaptive responses, reflecting the city's resilience to heat. Although air temperatures in Aariyakulam Park and Pannai Park were similar, visitors experienced different comfort levels due to variations in shade, vegetation, and wind exposure. At Aariyakulam Park, visitors exhibited physiological adaptations, such as acclimatization and thermoregulation, the body's natural adjustments in heart rate, skin temperature, and sweating, that help them tolerate heat. Over time, regular exposure to high temperatures allows people to perceive such conditions as "normal" or only slightly uncomfortable. In contrast, psychological adaptations were more evident in Pannai Park, where the presence of sea breezes, shaded plazas, and recreational amenities created a positive emotional response. People associated these settings with leisure and relaxation, which improved their comfort perception even under warm conditions.

Among all sites, Pannai Park's Sunken Tree Court provided the best overall comfort, combining dense shade, permeable surfaces, and effective natural ventilation. These findings demonstrate that well-designed blue–green environments can enhance both physical adaptation and psychological well-being, helping people cope better with heat in urban settings. The research highlights the need for climate-responsive, human-centred landscape design integrating trees, shaded seating, and coastal airflow corridors to strengthen comfort in public spaces. Future studies could expand this work through long-term monitoring, seasonal analysis, and behavioural modelling to better understand how people adapt physiologically and psychologically to changing climates in tropical cities like Jaffna.

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