The effect of tree planting pattern on thermal comfort of pedestrians in urban streets: case of Ananda Coomaraswamy Mawatha, Colombo, Sri Lanka

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Abstract

Street vegetation has an important impact on pedestrian thermal comfort, resulting in habitable urban street landscapes. As a result of industrialization and urbanization, unplanned developments along streets have become a cause of thermal discomfort for pedestrians. Since planting space is limited, proper arrangement is critical to improving Outdoor Thermal Comfort (OTC). The impact of diverse tree patterns on OTC has not yet been investigated.
This study employs numerical simulations using ENVI-met 5.5.1 Bio-met software and The Predicted Mean Vote at 1.5 m above ground level on a sunny day at 2 pm to understand how planting patterns affect microclimate and OTC at pedestrian level (1.5m) when using different 8 tree patterns are suggested within the selected Local Climate Zone (LCZ) in Colombo. There is pattern1 to 8 with the base case scenario. The research method is divided into four stages: On-site measurements, Modelling of the research area, Assessment of existing microclimatic and thermal comfort conditions, and the Comparison of the impact of planting pattern on microclimate and OTC. Changes in tree patterns have a significant impact on OTC in urban environments, affecting Air Temperature, Wind Speed, Mean Radiant Temperature, and relative Humidity. MRT and WS have been identified to be the most critical characteristics influencing thermal comfort. Pattern2 has a significant influence at the pedestrian level, providing the maximum comfort increase (0.9 PMV reduction) to reduce thermal discomfort, reduced canopy overlaps with reduced canopy distance and the use of small tree category trees to get to planting densities, enhanced homogenous shadow covering and ventilation, are recommended. Future studies should look into the cooling effect of native tree species. These findings can help urban designers and landscape architects improve microclimate and OTC in warm, humid cities.

Key Words*:* Urban Microclimate, Outdoor Thermal Comfort, Tree Patterns, ENVI-Met, Warm humid Colombo.

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1. Introduction

Urban climate change and rising ambient temperatures pose significant challenges for policymakers, particularly in warm-humid regions where outdoor thermal comfort (OTC) is a pressing concern. Despite the region's vulnerability to heat stress, research on OTC remains limited (Chatzidimitriou & Yannas, 2017; Taleghani et al., 2015). Increased urbanization exacerbates microclimatic changes, directly impacting pedestrian well-being through the urban heat island (UHI) effect. This phenomenon results from differences in energy balance and thermal characteristics between urban and rural areas (Marando et al., 2019). To mitigate the UHI effect, it is essential to create and maintain thermally suitable outdoor environments through urban morphology modifications and vegetation incorporation (Akbari et al., 1997; Norton et al., 2015). Urban design elements, including morphology, geometry, density, and vegetation arrangement, significantly affect OTC in warm-humid climates (Johansson & Emmanuel, 2006; Sharmin et al., 2015). Among these factors, urban space morphology, element orientation, and vegetation are critical for enhancing thermal comfort (Yahia & Johansson, 2014). Vegetation plays a crucial role in mitigating adverse urban microclimate effects, offering benefits such as reducing air temperature, providing shade, improving air quality, lowering noise levels, and blocking incoming solar radiation (Dimoudi & Nikolopoulou, 2003). In tropical regions with high solar radiation, vegetation is particularly effective in improving pedestrian thermal comfort (Taleghani, 2018a).

Green infrastructure is also vital in mitigating long-wave radiation exchange by blocking short-wave radiation from reaching surfaces, compared to ground covers (Shashua-Bar et al., 2011). While previous studies have addressed both macro and microscale climatic conditions, local land use planning is essential for enhancing the quality of context-specific environments (Kyttä et al., 2015). Perera & Emmanuel (2018) emphasized the importance of incorporating local-level planning in climate-responsive urban design to manage the UHI effect in tropical cities.

In Sri Lanka, a warm-humid tropical country, rising heat stress, documented through the Temperature Humidity Index (THI) from 1931-1961 to 2006-2016, has led to various health issues for urban residents (Nanayakkara & Nianthi, 2018). Colombo, the capital, faces heightened vulnerability due to rapid urbanization. Although classified as a "moderately comfortable" region, micro-level climatic conditions in Colombo have worsened due to increased building density, surface coverage, and insufficient vegetation. This study explores how tree planting patterns influence microclimate and OTC in tropical urban streets, aiming to provide solutions for improved environmental conditions.

2. Literature Review

2.1 Outdoor thermal comfort (OTC)

Daytime outdoor thermal comfort (OTC) is critical in urban areas, especially in warm-humid climates where solar radiation significantly impacts pedestrian comfort. This thermal discomfort often results from unplanned urban development, reduced vegetation, and increased hard surfaces. Thermal comfort is defined as a "state of mind expressing satisfaction with the thermal environment" (ISO 7730, 1990). The human body exchanges heat with its environment through conduction, convection, radiation, and evaporation, influenced by factors like clothing, activity level, temperature, humidity, thermal radiation, and wind speed (Lai et al., 2019). Urban geometry, surfaces, vegetation, and water bodies further shape the microclimate and thermal environment in urban streets (Zhao & Fong, 2017). Understanding OTC is complex due to the interplay of spatial and temporal factors affecting both physiological and psychological responses (Dimoudi & Nikolopoulou, 2003). This study examines the physical and physiological dimensions of OTC, essential for addressing urban heat discomfort.

2.2 tree pattern Strategies in Tropics to Enhance OTC Effect

In tropical regions, greening strategies are commonly employed to enhance outdoor thermal comfort (OTC) (Jamei et al., 2020). Emmanuel et al. (2007) demonstrated how tree placement, size, and type influence microclimate variables like relative humidity, wind temperature, speed, and direction by analyzing dependent factors such as greenery placement and tree dimensions. The effectiveness of tree pattern strategies varies based on location, context, and climate zone, as noted by Prajapati (n.d.). Trees offer shading and cooling through evapotranspiration, reducing surface temperatures and enhancing pavement performance (Priya & Senthil, 2021). Tree characteristics, such as crown size, leaf area index, and arrangement, influence the extent of shading and cooling effects (T.U.N. et al., 2020). Clustering vegetation arrangements has shown greater effectiveness in temperature reduction (Speak et al., 2020).

2. Research methodology

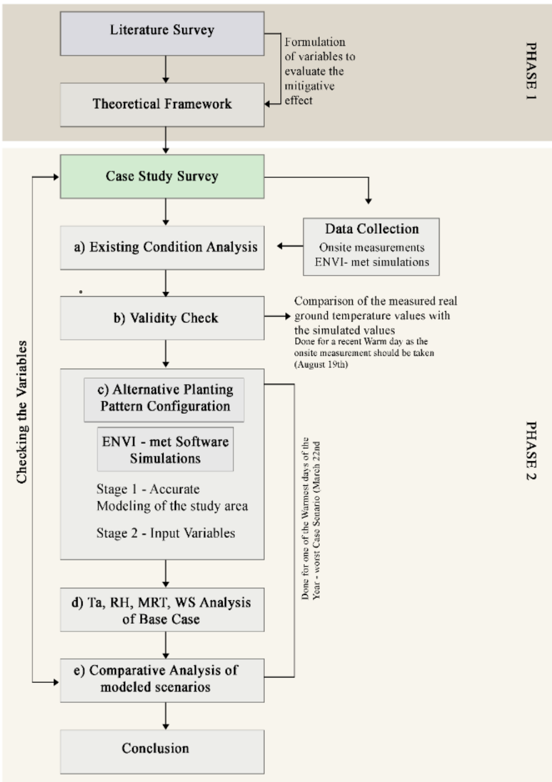


Fig.1: Methodology of Study; Compiled by Author

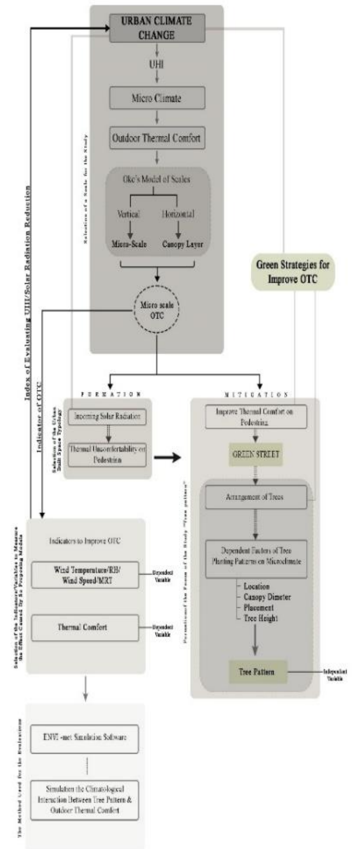
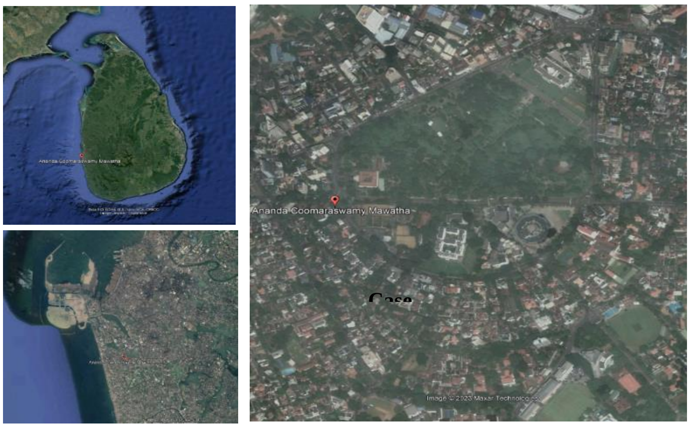


Fig.2: Theoretical Framework of the Study.

The research involved three stages: (1) onsite measurements, (2) base case OTC assessment using ENVI-met, and (3) impact evaluation of tree planting patterns on OTC. Micrometeorological CFD modeling was used to analyze various planting patterns in Ananda Coomaraswamy Mawatha, comparing their effects on outdoor thermal comfort via PET simulations.

3.1 Study area and climatic conditions

Colombo, characterized by a warm-humid climate, has an average annual temperature of 26.5°C and 2387 mm of rainfall, classifying it as a tropical rainforest (Af) according to the Köppen-Geiger system (Peel et al., 2007). The study focuses on Ananda Coomaraswamy Mawatha, the longest E-W oriented street in Colombo, located at 6°54'42.9"N, 79°51'18"E. This area is classified as a large low-rise Local Climate Zone (LCZ), with 48% of the Colombo municipal area in the compact low-rise LCZ and 23.7% in the large low-rise LCZ (Perera & Emmanuel, 2018). The site covers approximately 2562.99 m².



- Width of road = 21.28m
- Average building height on the northern edge = 9m
- Average building height on the southern edge = 9m
- Width of the northern sidewalk = 3.3m
- Width of the southern sidewalk = 1.9m
- Median strip = 4.57m
- Height of one floor = 3m

Fig.3: Study area Location of Ananda Coomarsawmy Mawatha) Location related to Colombo.

3.2 Method and Tools

Fieldwork design

Conducting an onsite measurement session, air temperature (Ta), relative humidity (RH), wind speed (WS), and wind direction (WD) were measured at 1.5m above ground level as inputs for the ENVI-met 5.5.1 simulation model. The height of 1.5m has the significant impact on human thermal comfort (Davtalab, Deyhimi, Dessi, Hafezi, & Adib, 2020; Morakinyo et al., 2020; Wang, 2006; Yin, Lang, Xiao, & Xu, 2019). The field measurements were taken on a clear, sunny day with no cloud cover. Measuring real-time onsite climate data utilizing HOBO MX2301A DATA LOGGER and ANEMOMETERS, The HOBO MX2301A was used to measure relative humidity and ambient temperature in each location. The data logger was pre-programmed to record data continuously every 10 minutes. as well as other comparable equipment, has been widely employed in various studies.

3.3 Micro-meteorological simulations

ENVI-met is a three-dimensional non-hydrostatic microclimate model designed to analyze the relationship of microclimate and urban design on a micro scale. Using fluid dynamics and thermodynamics factors such as wind speed and direction, air temperature, humidity, radiative fluxes, and pollution dispersion, the model computes microclimate elements during a diurnal cycle. ENVI-met simulation requires two input data sets: an input file and a main configuration file. In order to build the spatial features of the study area, such as geographical location, building height and material, soil and surface type, and vegetation, input file data is required. The maximum model size was limited to 50* 50*40 grids. Horizontal X- and Y-axes, a grid with a size of 1 m was adopted. 2 m was chosen for the grids on the Z-axis.

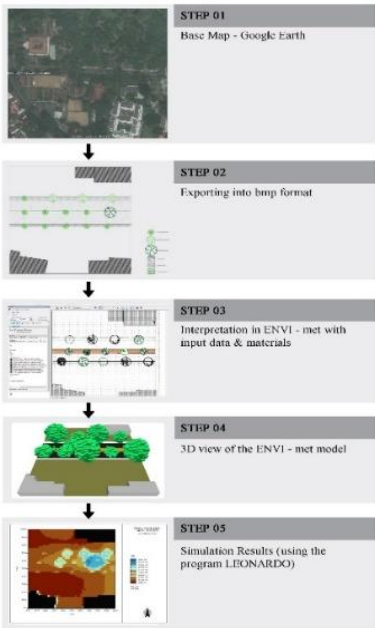


Fig.5: Procedure followed in Simulations; Source - Author

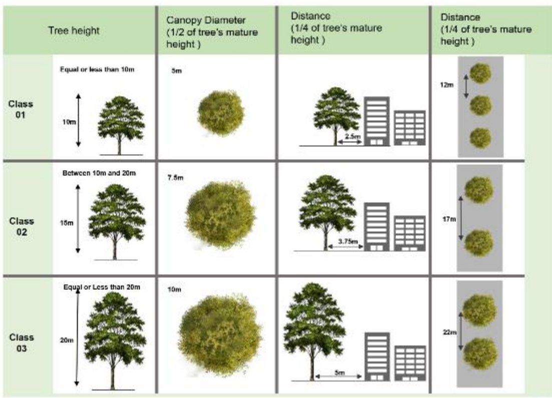
Factor	Considerations/Assumptions
1. Date	Except for the validity check, simulations were done on 19th August 2023 which is taken as one of the warmest dates of the year, yet the worst-case scenario.
2. Time	Simulations were done for 12 hours, from 9AM - 8AM, as SUHI shows a diurnal behavior.
3. Input Meteorological Data	Based on the historical average data of the Meteorological Station of Colombo - Katunayake Minimum Temperature - 23°C Maximum Temperature - 30°C Humidity - 65% - 96% Wind Speed - 2m/s
4. Location	Model rotation was done to match the grid North with actual conditions
5. Surface	The surface materials used were selected from the ENVI-met database which was assumed to be similar to the existing one. All the vegetation was modeled over a loamy soil material pallet considering it as the planting media.
6. Trees	As the ENVI-met database does not contain the Local species, certain substitutes were used. (For the proposed models all existing trees were removed & added new trees with the same characters) Existing - Deciduous, spherical trees Matching the prevailing characteristics Proposed - Deciduous, spherical, of 10m height & 10m crown diameter (Small) 10m height & 15m crown diameter (Medium) , 15 height & crown diameter 25 (Large)

Table 1: Simulation Considerations and Assumptions of the Study. Compiled by Author

3.4 Proposed Vegetation Options for ENVI – met simulations.

According to the codification of tree classes in relation to the width of sidewalks following cases identified. **Ananda Coomaraswamy** Street, suitable trees are divided into class 01, 02 and 03 as show in the below chart. Due to the limitation of the time same scenario and cases which minimum response for the thermal comfort have deselected and below mentioned final cases have selected to simulation process. All the possible cases for two sidewalks and median strip of the street and all the suitable cases for **Ananda Coomaraswamy** Street are highlighted

Table 2: Classification of Trees According to Height, Diameter and Distance Source: Rantzoudi et al., 2017



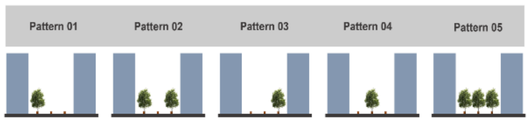
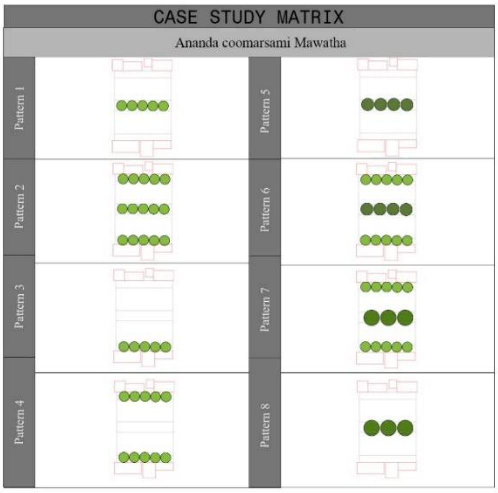
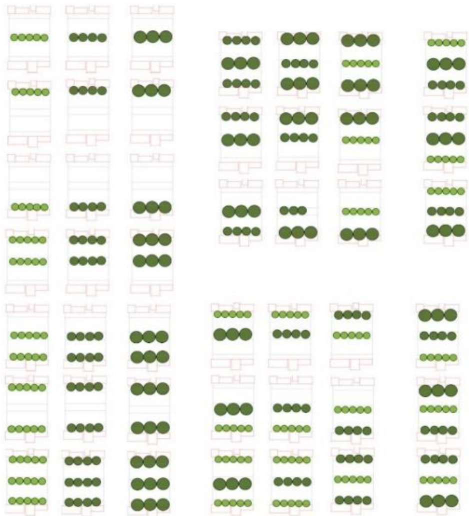


Fig.6: Street Tree Planting Pattern Compiled by Author

Table 3: Codification of Ananda Coomaraswamy Mawatha

Ananda Coomaraswamy Mawatha			
Sidewalk width		Tree category	
	Class 01	Class 02	Class 03
North; 3.3m			
South ;1.9			
Median; 4.57m			





3.5 Evaluation Indexes

Environmental variables such as wind temperature, relative humidity, wind speed, and solar radiation impact to human thermal comfort in outdoor environments. These parameters are conceived of as thermal standards capable of determining an individual's level of comfort in specific weather conditions. (Ghani, Mahgoub, Bakochristou, & ElBialy, 2021) The researched indices under consideration include a number of factors that are either directly measured or offered by international standards

4. Results and Findings

4.1. Validation of ENVI -met.

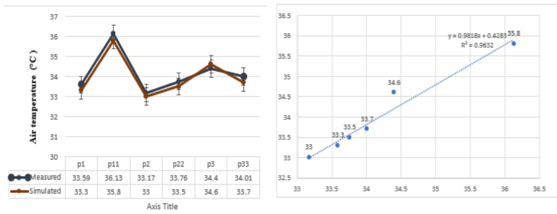


Fig.7: Validation Results a) Location vs temperature

The study confirmed the model's reliability with an R^2 value of 0.96, showing no significant difference between observed and simulated data from August 19, 2023.

4.2. Microclimate Comparison with Base Case

In the microclimate analysis comparing various planting patterns with the base case, significant variations were observed in air temperature, relative humidity, wind speed, and mean radiant temperature (MRT). The orientation of the site, with an East-West street canyon, exposed the area to continuous solar radiation, leading to an increase in air temperature across all proposed patterns. Pattern 2, with minimal exposure to afternoon solar radiation, exhibited the lowest increase in air temperature, while Patterns 3 and 4, with less canopy coverage, experienced the highest rises in temperature, indicating these patterns are less effective in cooling the environment. Relative humidity, crucial in warm-humid areas, varied notably among the patterns. Pattern 2, featuring medium-sized trees and closely spaced walkways, resulted in the highest relative humidity at 69.375%, whereas Pattern 4 achieved the lowest at 48.94%.

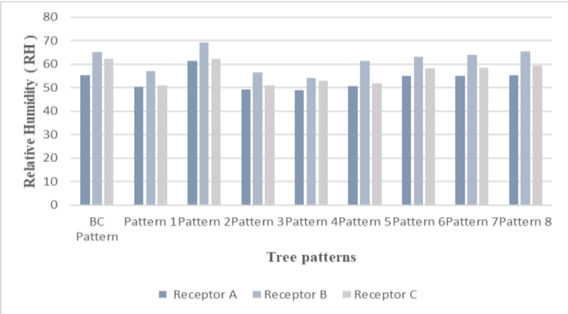


Fig.8: RH comparison of different planting pattern at Receptors for 22nd March 2023 (Worst-case) ; Source - Author

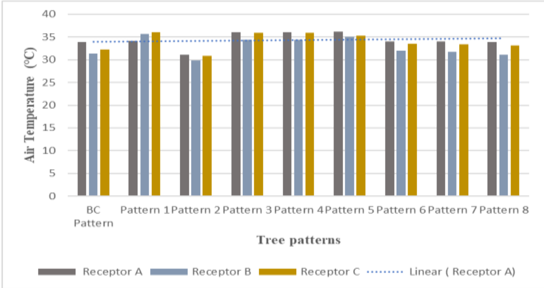


Fig.9: receptor columns of outdoor air temperature comparison of different planting patterns at 1.5m height. (The upper and lower bounds of the columns indicates the lower and upper quartile (Q1 and Q3) of the Ta values, the whiskers 5th and 95th percentile

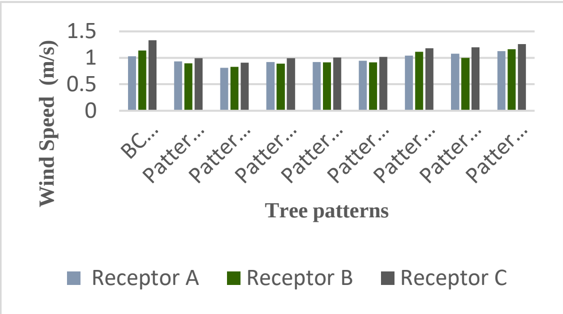


Fig.10: wind speed comparison of different planting pattern at Receptors for 22nd March 2023 (Worst-case); Source - Author

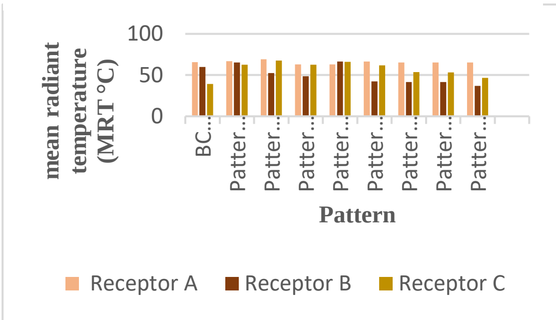


Fig.11: MRT comparison of different planting pattern at Receptors for 22nd March 2023 (Worst-case); Source - Author

The difference in humidity reduction between Pattern 2 and the base scenario was approximately 2%. Wind speed improvements were observed based on different tree patterns, with Pattern 8 showing the best performance, increasing the mean wind speed by 0.016 m/s. The base case and Pattern 7 showed improvements of 0.147 m/s and 0.07 m/s, respectively. Patterns 1, 2, 3, and 4, with denser planting, resulted in lower wind speed increases due to obstructed wind flow caused by overlapping canopies. Finally, mean radiant temperature (MRT), reflecting the combined effect of solar and thermal radiation, showed that Pattern 1 achieved the highest improvement in MRT (10.091°C), with Patterns 2 and 4 showing increases of 8.19°C and 10.3°C, respectively. These findings highlight the varying impacts of planting arrangements on microclimatic conditions and their implications for environmental comfort.

4.3. Comparison of thermal comfort conditions – PMV

The predicted mean vote (PMV) was calculated at pedestrian level (1.5m) using simulated air temperature, relative humidity, wind speed, and mean radiant temperature (MRT) for the base case and proposed Tree pattern scenarios. Figure 16 illustrates the mean PMV (outside thermal comfort) values for various circumstances at 14.00.01 hr. In comparison to the current scenario, tree patterns 2 and 6 have a positive impact on outdoor thermal comfort levels, with mean PMV values increasing by 0.02 °C and 0.03 °C, respectively. The existing planting arrangement (base scenario) is slightly similar to Pattern2 and Pattern6, however there are more trees in all sidewalks and the median strip. As a result, the average PMV value is close to the base case.

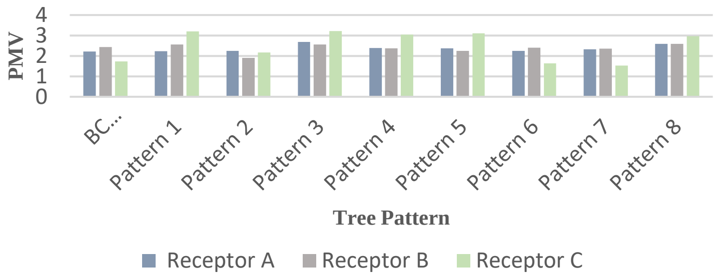


Fig.12: PMV comparison of different planting pattern at Receptors for 22nd March 2023 (Worst-case); Source - Author

4.4. OTC Comparison of receptors – PMV

Fig.13: Coomaraswamy Mawatha - Receptor A: PMV Evaluation 9.00am to 20.00pm; Source - Author

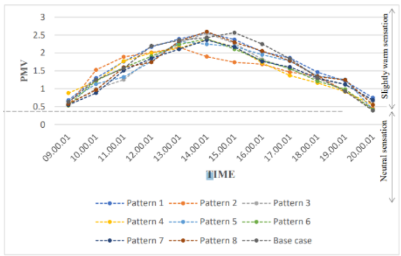


Fig.14: Coomaraswamy Mawatha - Receptor A: PMV Evaluation 9.00am to 20.00pm; Source - Author

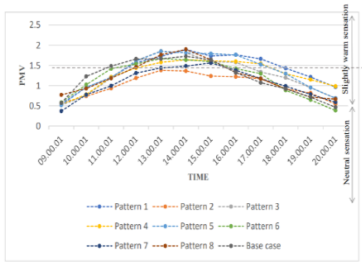


Fig.15: Coomaraswamy Mawatha - Receptor C : PMV Evaluation 9.00am to 20.00pm ; Source - Author

- **Receptor A:** Psychophysical thermal comfort at Receptor A (southern sidewalk) was assessed using the PMV index in Bio-met software, considering air temperature, MRT, wind speed, and humidity. PMV values ranged from 'slightly warm' to 'warm,' with higher morning values indicating increased pedestrian heat stress. Pattern 3 had the highest PET due to trees on the opposite sidewalk, while Pattern 2 and Pattern 6, featuring smaller trees on sidewalks and median strips, had the lowest PMV values, indicating better thermal comfort. Reducing tree size and providing more shading improved comfort, but Pattern 3's PMV peaked around 14:00 due to exposed surfaces, suggesting that additional tree coverage could enhance comfort further.
- **Receptor B:** At Receptor B (median strip on Ananda Coomaraswamy Mawatha), PMV values were slightly warm from 08:00 to 11:00, with significant increases between 12:00 and 14:00, peaking at 1.5 to 2.5. Patterns 2, 6, and 7 showed similar PMV values, with Pattern 4 providing better comfort at noon. Highest PMV values occurred with trees on the median strip, peaking midday but declining after 13:00 due to shading from large canopies. Exposed surfaces increased air temperature and decreased comfort.
- **Receptor C:** At Receptor C (northern sidewalk), PMV values peaked around 12:00 and 16:00 with a recession in between. Lower PMV values compared to A and B were observed due to nearby buildings. Patterns 5, 1, and 8, with tree lines on the median strip, showed the highest PMV, while Pattern 2 had the lowest PMV and was most comfortable. Patterns 2 and

6 provided the best comfort around midday, with PMV values for Pattern 2 indicating slight warmth and comfort.

4.5. Discussion

The study examined the impact of outdoor thermal comfort (OTC) through tree planting patterns on urban road networks, focusing on how these patterns influence micrometeorological conditions like air temperature, wind speed, mean radiant temperature (MRT), and relative humidity. Simulation studies indicated that strategically placing small to medium-sized trees to avoid canopy overlaps can significantly cool urban environments by reducing afternoon solar radiation on surfaces and buildings (De Abreu-Harbich, Labaki, & Matzarakis, 2015). In semi-arid climates, denser tree planting was found to be more effective in reducing Predicted Mean Vote (PMV) than merely lowering outdoor air temperature (Q. Zhao, Sailor, & Wentz, 2018).

In warm-humid regions, densified tree patterns can reduce air temperature but may not improve PMV due to decreased wind speed and reduced skin evaporation rates, negatively affecting thermal comfort (Hsieh, Jan, & Liman, 2016). Patterns 2 and 6 were particularly effective in improving OTC by lowering PMV, as they minimized horizontal surfaces exposed to solar radiation, whereas patterns 8 and 3 were less effective in these climates. Properly aligned tree arrangements, such as patterns 8, 5, and 3, can enhance cooling by creating larger shaded areas while avoiding canopy overlaps (De Abreu-Harbich et al., 2015).Wind speed was identified as a critical factor in enhancing microclimates in warm-humid areas, with patterns 1, 3, and 4 resulting in the lowest wind speeds. Pattern 3 was the least favorable for wind speed, MRT, and PMV, even though it did not significantly affect air temperature. This finding supports previous research that highlights the importance of MRT and wind speed in influencing thermal comfort in warm-humid environments (Morakinyo & Lam, 2016; Morakinyo et al., 2020). The study emphasizes aligning tree patterns with wind direction to improve thermal comfort (Abdi, Hami, & Zarehaghi, 2020).

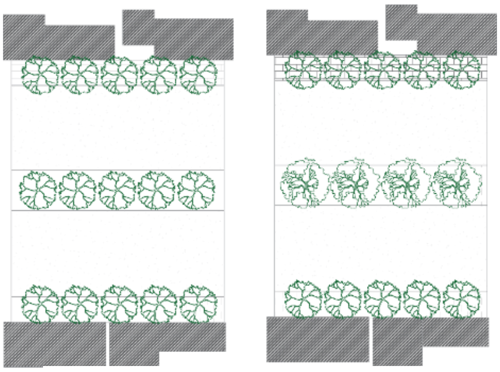
Finally, relative humidity was influenced by tree planting patterns, with higher wind speeds linked to greater reductions in humidity through evapotranspiration. The study recommends strategies like evenly distributed shade, minimal distances between trees, and enhanced ventilation to optimize PMV in warm-humid urban areas (Q. Zhao et al., 2018). While acknowledging the limitations of the ENVI-met model, the research offers valuable insights for urban planners in designing tree planting patterns to enhance microclimatic conditions and improve thermal comfort, especially in warm-humid climates.

5. CONCLUSION

This research emphasizes the pivotal role of tree planting patterns in improving microclimate and pedestrian thermal comfort in warm-humid cities like Colombo. Given the limited planting space and extensive hard surfaces in Colombo's urban areas, optimizing tree planting pattern is crucial for maximizing cooling benefits. Microclimate simulations using validated ENVI-met lite software demonstrated that strategic tree planting significantly impacts air temperature, wind speed, mean radiant temperature (MRT), and relative humidity (RH), thus enhancing outdoor thermal comfort (OTC). The study found that homogeneous canopy coverage notably reduces the Predicted Mean Vote (PMV), shifting conditions from very hot to warm. Among the proposed patterns, pattern 4, with rows of small trees on sidewalks, showed the best results for thermal comfort. The study suggests focusing on tree patterns that provide extensive shading, such as pattern 2, to improve comfort and support sustainable urban planning (De Abreu-Harbich et al., 2015; Q. Zhao et al., 2018).

RECOMMENDATION

This research highlights the importance of optimizing tree planting patterns to improve pedestrian thermal comfort in urban streets. Key recommendations include avoiding overlapping canopies, enhancing ventilation, and aligning tree patterns with wind direction. Future studies should validate these findings with field observations.



Pattern 2 Pattern 6

Fig.16: most suitable options for the Ananda Coomaraswamy Mawatha

Ananda Coomaraswamy Mawatha

According to mentioned recommendations lowest PMV value reached in Pattern2. pattern 2 equals to pattern6 which varies by 1.3 °C from Base Case scenario

I. 1. Providing small size trees for north, south side walk and median strip of the street (spherical, deciduous 5m height and crown diameter), if followed
II. the pattern2 layout the PMV value could be reduced by 0.02.
III. Providing small size trees for north, south side walk spherical, deciduous 5m height and crown diameter) and median strip consist of medium size trees of the street (spherical, deciduous 10m height and crown diameter), if followed the pattern layout the PMV value could be reduced by 0.03.

ACKNOWLEDGMENTS

This work is supported by the University of Moratuwa in partially funding the research publication.

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