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IMPACT OF NEIGHBORHOOD MORPHOLOGY IN TROPICAL CLIMATES: A CASE STUDY OF THE TRADITIONAL NEIGHBORHOODS OF KANYAKUMARI, INDIA

IMPACTO DE LA MORFOLOGÍA DEL VECINDARIO EN EL CLIMA TROPICAL: UN ESTUDIO DE CASO DE LOS BARRIOS TRADICIONALES DE KANYAKUMARI, INDIA

IMPACTO DA MORFOLOGIA DOS BAIRROS EM CLIMAS TROPICAIS: UM ESTUDO DE CASO DOS BAIRROS TRADICIONAIS DE KANYAKUMARI, ÍNDIA

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ABSTRACT

The morphology of the built environment interacts with the surrounding thermal environment. Thermal interactions affect a neighborhood's energy demand and thermal comfort. The extreme temperatures owing to climate change demand intervention reciprocating in urban heating. Thus, this study analyzed the thermal interaction between morphology and the thermal environment. The study was conducted in the tropical city of Kanyakumari, located in India. The influence of aspect ratio, sky view factor, green cover ratio, and building cover ratio on the Universal Thermal Climate Index was studied. A quantitative analysis of the morphological variables was conducted to establish a relationship with the comfort variable. The aspect and green cover ratios positively correlated with the climate index. In contrast, the sky view factor and building cover ratio had a negative relation with the index. However, when vegetation was introduced in the streets, the interaction between the aspect ratio and the index was reversed, where an increase in aspect ratio reduced the comfort in the canyon by introducing vegetation.

Keywords
morphology, residential area, climate, tropical zones

RESUMEN

La morfología del entorno construido interactúa con el ambiente térmico circundante. Las interacciones térmicas afectan la demanda energética y el confort térmico de un vecindario. Las temperaturas extremas debido al cambio climático exigen una intervención para reciprocar la calefacción urbana. Por lo tanto, este estudio analizó la interacción térmica entre la morfología y el ambiente térmico. El estudio se llevó a cabo en la ciudad tropical de Kanyakumari, en la India. Se estudió la influencia de la relación de aspecto, el factor de vista del cielo, la relación de cubierta verde y la relación de cubierta edificada en el Índice Climático Térmico Universal. Se realizó un análisis cuantitativo de las variables morfológicas para establecer una relación con la variable de confort. Las relaciones de aspecto y cubierta verde se correlacionaron positivamente con el índice climático; por el contrario, el factor de vista del cielo y la relación de cubierta edificada tuvieron una relación negativa con el índice. Sin embargo, cuando se introdujo vegetación en las calles, la interacción entre la relación de aspecto y el índice se invirtió. Un aumento en la relación de aspecto redujo el confort en el cañón al introducir vegetación.

Palabras clave
morfología, zona residencial, clima, zonas tropicales

RESUMO

A morfologia do ambiente construído interage com o ambiente térmico circundante. As interações térmicas afetam a demanda energética e o conforto térmico de um bairro. As temperaturas extremas decorrentes das mudanças climáticas exigem intervenções que repercutem no aquecimento urbano. Assim, este estudo analisou a interação térmica entre a morfologia e o entorno térmico. O estudo foi realizado na cidade tropical de Kanyakumari, localizada na Índia. Foi estudada a influência da relação de aspecto, do fator de vista do céu, da relação de cobertura verde e da relação de cobertura dos edifícios no Índice Climático Térmico Universal. Realizou-se uma análise quantitativa das variáveis morfológicas para estabelecer uma relação com a variável de conforto. As proporções de aspecto e cobertura verde correlacionaram-se positivamente com o índice climático. Em contrapartida, o fator de vista do céu e a proporção de cobertura dos edifícios tiveram uma relação negativa com o índice. No entanto, com a introdução de vegetação nas ruas, a interação entre a proporção de aspecto e o índice foi invertida em áreas onde um aumento na relação de aspecto costumava reduzir o conforto no cânion.

Palavras-chave:
morfologia, área residencial, clima, zonas tropicais

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INTRODUCTION

Indian cities are undergoing significant and continuous development. Currently, the key concern in the design of cities is to mitigate urban heating (Pattacini, 2012) and respond to climate change. There are several aspects involved in this. The energy balance in the canopy layer determines the resultant thermal environment. The heat gain through solar radiation and anthropogenic factors in the absence of advection is equal to heat loss through convection, evaporation, and heat storage. The canyon geometry and thermal properties influence these thermal exchanges in the canopy layer (Oke, 1982). Thus, an optimum built geometry and surface configuration ensure climate-responsive neighborhoods (Oke et al., 1991). However, the urban configuration determines the mitigation strategy. Hence, the design strategy cannot be generalized (Golany, 1996).

Thermal comfort and reducing outdoor air temperature are essential for developing sustainable neighborhoods (Emmanuel & Fernando, 2007). The immediate morphology alters the microclimate of an open space and its interaction with the indoor environment. The built morphology and the thermal environment are interdependent. The Bureau of Energy Efficiency identified that the influence of extreme temperatures combined with economic growth increased energy demand to attain comfort (Bureau of Energy Efficiency, 2023). Hence, the optimum design of the neighborhood morphology aims to create a comfortable environment and reduce energy demand.

Earlier studies critically analyzed the indoor climate to reduce energy demand and improve comfort and air quality, while the current studies highlight outdoor settings for the same (Shafaghat et al., 2016). Hence, a holistic approach is essential to address indoor and outdoor environments as they have a reciprocal relationship.

In a thermal environment study, mean radiant temperature (MRT) needs to be analyzed in addition to air temperature. The analysis of the MRT will ensure comfort (Emmanuel & Fernando, 2007). Hence, a thermal comfort parameter that addresses the effect of solar radiation on perceived human comfort needs to be considered.

The tropics have been analyzed for their relationship between street geometry and microclimate. However, there are fewer studies on the coastal zones of the tropics. Similarly, the intercity microclimate variation has not been discussed (Shafaghat et al., 2016). Although studies address the tropical climate, urban design strategies cannot be generalized (Emmanuel & Fernando, 2007). Therefore, an *in-situ* measurement of the neighborhoods in the city will ensure a sustainable built environment.

The study of morphology for its thermal performance often addresses building, street, and landscape configurations simultaneously (Emmanuel & Johansson, 2006; Sun, 2011; Boukhabla et al., 2013; Tsoka et al., 2020). The positive effects of vegetation on the thermal environment are evident (Tsoka et al., 2017; Lassandro et al., 2019; Tsoka et al., 2020; Zhou et al., 2021). Hence, studies to optimize buildings and streets are critical for improved thermal conditions. In this study, the morphology selected reflected built environment configuration through aspect ratio, sky view factor, green coverage ratio, and building cover ratio. Even though the aspect ratio and sky view factor convey the degree of closure of the urban canyon, the study of the sky view factor was crucial as it can be altered easily (Zhu et al., 2022).

This study used traditional row house settlements in Kanyakumari as a case study to explore the relationship between morphological features and the thermal environment in a tropical setting. The thermal environment was studied using comfort variables at the street and neighborhood scales. The research identified the most effective design for a sustainable neighborhood through statistical analysis in a tropical context.

The analysis was conducted in Nagercoil, a city in Kanyakumari, India. It is located at 8.1° N latitude and 77.4° E longitude. The cultural and geographic features influenced the evolution of the built morphology of Kanyakumari. The city falls under a Tropical wet and dry (Aw) climate according to the Köppen-Geiger Classification and a warm and humid climate according to the National Building Code (NBC, 2016). The city experiences an annual average temperature of 27.2°C, a minimum of 23°C in February, and a maximum of 33.2°C in September. The adaptive thermal comfort was within the range in most months except April. (Figure 1a) The average annual relative humidity was 78.54%, with a minimum of 43% in February and a maximum of 99% in September. The humidity levels were mainly above the thermal band. (Figure 1b) The wind predominantly flows from west to east, reaching up to 5 on the Beaufort Scale. (Figure 1e) A slight wind movement below 1.5m/s can be observed from all directions. (Figure 1f) The city experiences clear skies between January and April. (Figure 1c) In April, heat stress was observed 97% of the time. (Figure 1d) The absence of dense cloud cover during April creates thermal stress. Hence, this study addressed the month with prolonged thermal stress (Betti et al., 2024).

METHODOLOGY

The study intended to establish a relationship between morphology and the thermal environment of Kanyakumari. The traditional neighborhoods of the city were selected for the study. These neighborhoods had row houses facing either north or south. Hence, the principal streets were along the east-west axis. The row houses and north-south orientation reduced heat gain inside the houses (Shankar

Figure 1. Weather Profile of Kanyakumari. Source: Betti et al. (2024)

Table 1. Methodology. Source: Prepared by the authors.

Aim	Activity	Outcome	Details
Identify	Literature Review	Morphological Variables	Aspect Ratio (H/W)
			Sky View Factor (SVF)
			Green Cover Ratio (GCR)
			Building Cover Ratio (BCR)
		Thermal Environment Variables	Air Temperature 1.5 m
			Globe Temperature
			Relative Humidity
			Wind Movement 1.5 m
	Preliminary Study	Neighborhoods	Kottar (N-1)
			Vadeeswaram (N-2)
			Vadasery (N-3)
Select	Neighborhoods	Orientation	East-West Streets
		Aspect Ratio	Shallow (H/W < 1)
			Narrow (H/W > 1)
		GCR	GCR < 10
			GCR > 10
	Thermal Environment	Comfort Variable	Universal Thermal Climate Index (UTCI)
Process	Field Measurement	Air Temperature	Testo 440 Climate Measuring Instrument and 100 mm Ø Vane Probe
		Globe temperature	Heat Stress WBGT Meter
		Relative Humidity	Heat Stress WBGT Meter
		Wind Movement	Testo 440 Climate Measuring Instrument and 100 mm Ø Vane Probe
		Sky View Factor	Google Street View Application
Analyze	Statistics	Descriptive	Box Plots
			Scatter Plots

& Sundaram, 2023). This morphology exposed the streets to the intense solar radiation. Traditionally, these streets had trees, which were later removed to lay roads. This deteriorated the outdoor thermal environment. This character of the morphology is present only in Vadasery (N-3). Thus, comparing the thermal environment in these neighborhoods will ensure an optimum design strategy for the neighborhoods of Kanyakumari. The city experiences moderate air temperatures, high relative humidity, and wind movement. The weather data indicates that the conditions are ideal throughout the year. However, significant discomfort was also evident during April. The intense solar radiation causes heat gain and needs to be addressed.

A field investigation of three residential neighborhoods was conducted in April 2024 and was quantitatively analyzed. The variables for the study were derived from the literature review. The aspect ratio is the average height divided by the width of the street at a given point of measurement. The sky view factor is the portion of the visible sky to the total sky area from a specific point. These are three-dimensional variables that represent the exposure of the canyon to incoming radiation and wind movement. In two-dimensional variables, the green cover ratio is the fraction of landscaped area to the total area, while the building cover ratio is the ratio of built area to the total area. The green cover alters the thermal environment through evaporative cooling and shading. The built fraction provides shading, and the material property responds to the incoming radiation through stored heat and reflected radiation. The influence of aspect ratio, sky view factor, green cover ratio, and building cover ratio on the Universal Thermal Climate Index movement was analyzed. The field measurements taken at 1.5m and 3m were used to calculate the UTCI. The

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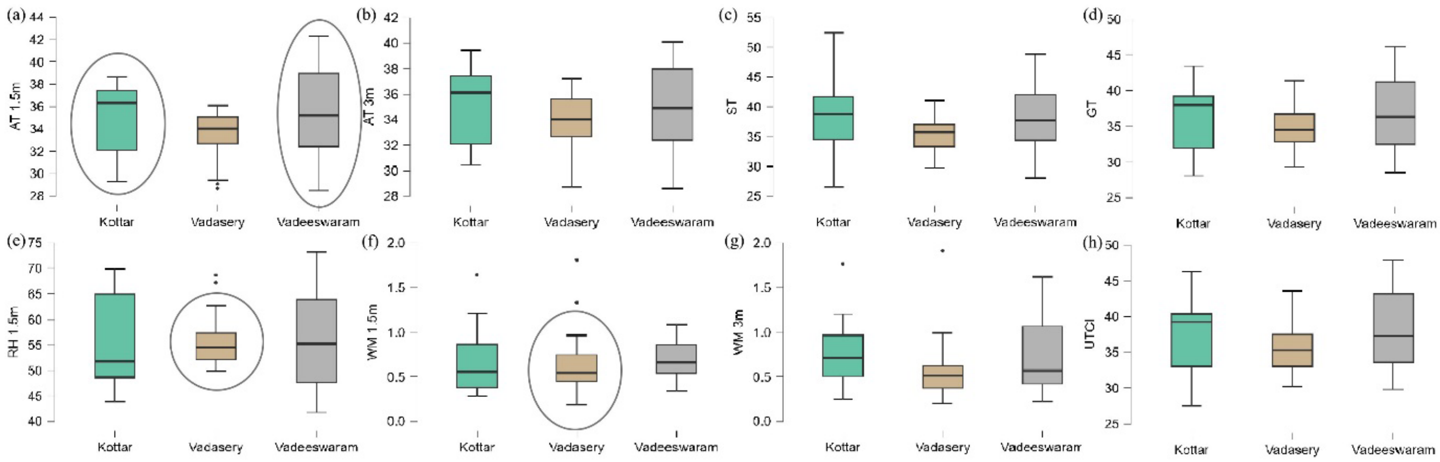

Figure 2. Microclimate Profile of the Neighborhoods. Source: Prepared by the authors.

mixed economic profile of the residential neighborhood ensures similar heat gains through devices and minimal vehicular movement. Hence, the impact of anthropogenic heat was not addressed. A previous study had found no significant difference between the aspect ratios of 1, 2, and 3 (G. Chen et al., 2020). Hence, streets were divided into aspect ratios of less than one and more than one for the analysis. The workflow of the study is described in Table 1.

NEIGHBORHOOD MORPHOLOGY

The neighborhoods are 20 km inland from the sea and surrounded by hills. The neighborhoods were selected based on their similarities in the orientation of streets. The selected neighborhoods were 1.5 km north of each other to ensure similar climatic conditions. The main streets of the neighborhood were aligned on the east-west axis. The intersections connecting them were in a north-south direction. Based on the documented morphological character, the aspect, and green coverage ratios were divided into categories. The streets were used to dry rice grains and yarn in N-1 before extensive development. The streets of N-2 are wide to accommodate processions during festivals. Hence, the size of the street allowed solar radiation and maximum footfall. The street character of N-3 was significantly different from N-1 and N-2 due to trees in the center of the streets. The buildings in the neighborhood were either two or three-story modern or traditional sloped-roof row houses. Hence, the height of the building ranged from 5m to 9m and had a maximum aspect ratio of three.

FIELD MEASUREMENT

April experiences a prolonged duration of heat stress. Hence, the field measurements were taken during this period. The data was recorded between 6 am and 6 pm every three hours. In total, 12 points were analyzed in the city. Neighborhoods 1, 2, and 3 had five, four, and three points, respectively. The measurements were taken at 1.5m to consider the pedestrian level comfort. The instrument was acclimatized for each point and recorded for 5 minutes. The radius of influence of 30 m, 40 m, and 50 m was analyzed in a preliminary analysis. The 50 m radius of influence was found to be more effective. The previous studies analyzed 25m, 50m, 56m, 75m, 100m, 125m, and 565m and found a 50 m radius of influence appropriate (Krüger & Givoni, 2007; Jusuf & Hien, 2012). The neighborhood was mapped for green coverage ratio (GCR), building cover ratio (BCR), and open space ratio (OSR). Since the open space ratio was similar in all the neighborhoods, only GCR and BCR were analyzed.

The air temperature and wind movement were measured through Testo 440 – Climate Measuring Instrument with a 100 mm wireless vane probe. The globe temperature and relative humidity were measured using the TM-188d – Heat Stress WBGT Meter. After processing the image collected through the Google Street View Application, the sky view factor was calculated from fish-eye images through RayMan Pro Version 3.1 (Shankar & Marwaha, 2023). The mean radiant temperature (MRT) was calculated using the formula derived for a 40mm black globe (Vanos et al., 2021; Ouyang et al., 2022). The air temperature, wind movement, relative humidity, and MRT were used to calculate UTCI from its official website.

RESULT AND ANALYSIS

A statistical analysis was conducted to understand the relationship between the morphological variables and the thermal environment. The thermal environment was analyzed through microclimate variables and a comfort variable. The microclimate variables addressed were air temperature, globe temperature, wind movement, and relative humidity. The universal thermal climate index was used to analyze comfort. The analysis was conducted in JASP (JASP Team, 2024).

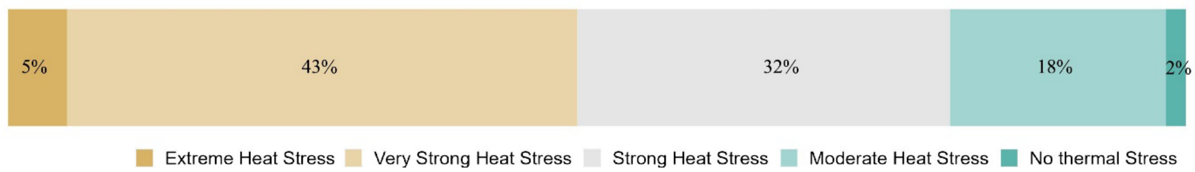

Figure 3. Distribution of UTCI category in the neighborhoods. Source: Prepared by the authors.

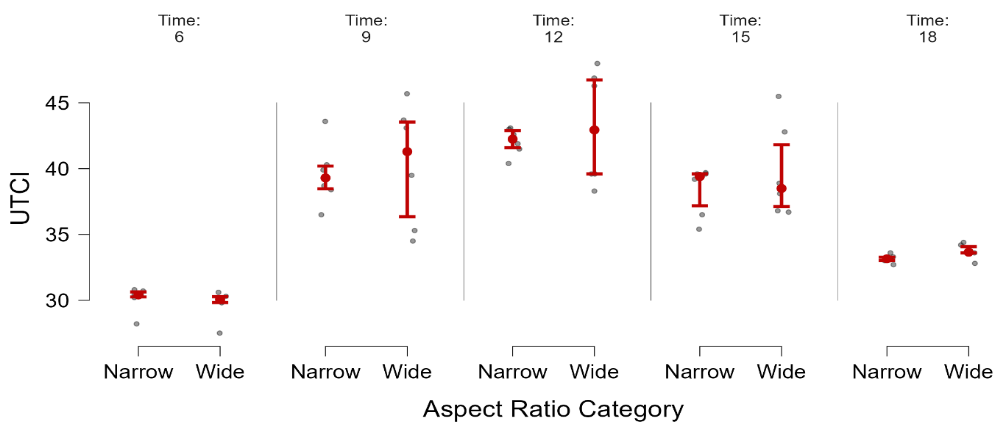

Figure 4. Impact of Aspect Ratio. Source: Prepared by the authors.

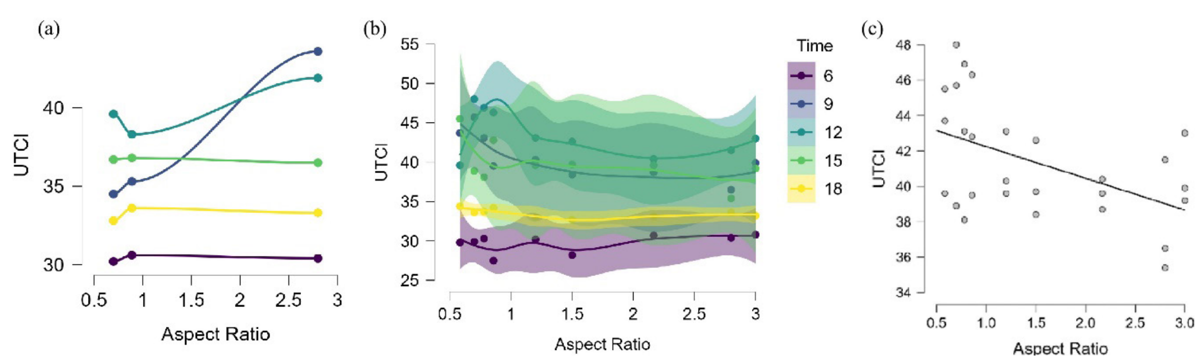

Figure 5. Time series data of Aspect Ratio (a) N-3 (b) N-1 and N-2 (c) Pearson's Correlation for N-1 and N-2. Source: Prepared by the authors.

THE NEIGHBORHOOD

All the neighborhoods showed a similar trend for temperature parameters, as observed in Figure 2. N-3 had a lower thermal range, while N-1 and N-2 experienced the lowest and highest temperatures (Figure 2a, b, c, and d). Hence, N-3 performed better than the other neighborhoods. Similarly, the relative humidity had a higher thermal range in N-1 and N-2, while it was consistently higher in N-3 (Figure 2e). The wind movement was comparatively lower in N-3 (Figure 2f). The mean UTCI suggested that the thermal comfort conditions were better in N-3, followed by N-2 and N-1 (Figure 2h). The UTCI categories were plotted according to their frequency in the neighborhoods in Figure 3. A significant difference from the weather data was evident. In contrast to the weather data, the neighborhoods experienced very strong heat stress of 43% instead of 28.6% (Figure 1), and the city did not experience extreme heat stress in the weather data. Hence, an *in-situ* measurement of the neighborhood will consider the prevalent thermal environment in the neighborhoods of Kanyakumari (Figure 3).

ASPECT RATIO

The two aspect ratio categories were analyzed for their effect on the thermal comfort variable. The wide canyons experienced a larger thermal range, while the narrow ones had a smaller one. The UTCI was higher for wide canyons than for narrow canyons. However, the 6 am data had lower UTCI for wide canyons than

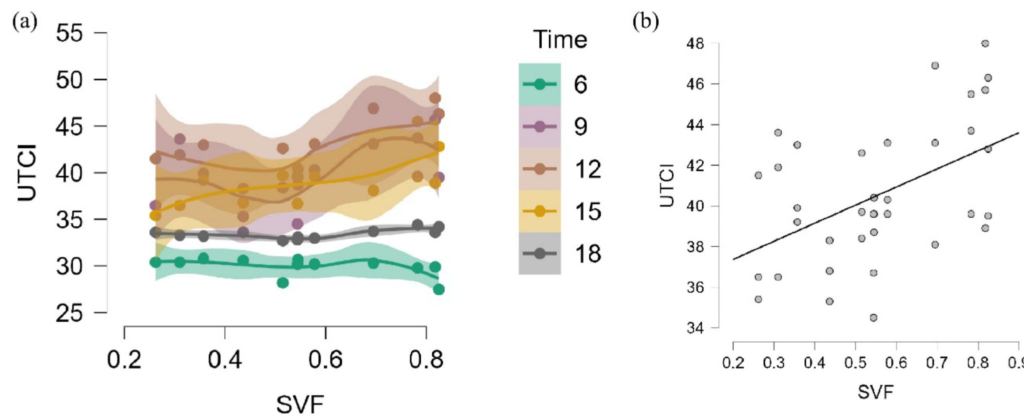

Figure 6. Time series data for all the neighborhoods and correlation plot. Source: Prepared by the authors.

for narrow canyons. The increased exposure in wide canyons enabled a better thermal environment at night. Hence, narrow canyons performed better than wide canyons during the daytime (Figure 4).

The continuous values of the aspect ratio were analyzed to derive the trends (Figure 5). Since the N-3 significantly differed in its thermal range and distribution, it was analyzed separately (Figure 5a). The scatter plots suggested a nonlinear relationship between UTCI and aspect ratio. The graph suggested a minimal change in the 6 am and 6 pm data concerning the aspect ratio (Figure 5b). In N3, the 9 am and 12 pm data highlighted the temperature increase with an increase in aspect ratio. Simultaneously, in N-1 and N-2, an increase in aspect ratio decreased temperature during 9 am, 12 pm, and 3 pm. The contrasting relationship of UTCI between neighborhoods was due to the influence of vegetation. A higher aspect ratio changes the temperature quickly due to increased exposure. However, the presence of vegetation in a narrow canyon captures heat. Hence, shallow canyons were ideal with vegetation, and narrow canyons were ideal without intensive vegetation in the street canyon.

The 6 am and 6 pm data did not show a significant difference. Hence, a correlation analysis was conducted for measurements at 9 am, 12 pm, and 3 pm. Karl Pearson's correlation was conducted as the UTCI had a p-value of 0.269, greater than 0.05 for N-1 and N-2. The Pearson's r was -0.497 with a p-value of 0.008. This suggests a negative relation of (0.497^2) 24.7%, and the null hypothesis can be rejected at a significance level of 1%. Hence, the aspect ratio should be higher for improved comfort in the streets during the daytime. However, the significant effect of shading from the trees played the most crucial role in reducing UTCI. Thus, improved comfort can be achieved through building structure or vegetation shading (Figure 5c).

SKY VIEW FACTOR

The relation between SVF and UTCI was analyzed for all the neighborhoods. A slight increase in UTCI can be observed between 9 am and 3 pm. Figure 6a shows a reduction in UTCI between 0.4 and 0.6 at 9 am and 12 pm. Also, there was no significant change in the 6 am and 6 pm data. Hence, the morning and evening data were omitted for further analysis (Figure 6a). The UTCI was normally distributed with a p-value of 0.089. Pearson's Correlation, a parametric test, was conducted since the p-value was greater than 0.05. The correlation analysis suggested a Pearson's r of 0.489 with a p-value of 0.002. Hence, there is a ($0.489^2 = 0.239$) 23.9% positive relationship with a 1% significance level. The daytime UTCI will increase with an increase in the sky view factor (Figure 6b). Thus, the sky view factor of more than 0.6 is detrimental to the daytime thermal environment.

GREEN COVER RATIO

The green coverage ratio was analyzed based on two categories. The GCR greater than 10% has a gradual increase in UTCI. However, the increase was instantaneous when the GCR was less than 10%. The maximum temperature was experienced at noon when the GCR was less than 10%. The nighttime temperature was slightly higher when GCR was greater than 10% (Figure 7). The thermal range was higher in higher green coverage due to differential heating in the neighborhood. A higher green coverage ratio positively affected the daytime thermal environment. The maximum green coverage studied in this analysis was only 20%. Hence, a higher green coverage ratio needs to be analyzed.

The relationship between green coverage and UTCI was analyzed over time. The 6 am and 6 pm data showed no significant trend (Figure 8a). However, the data between 9 am and 3 pm showed a decrease in UTCI with an increase in GCR (Figure 8b). The 9 am and 12 pm data followed

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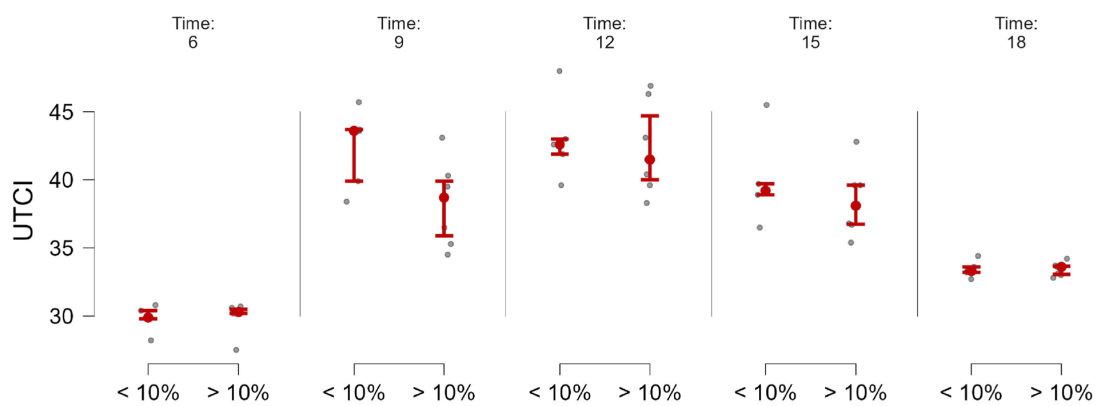

Figure 7. Impact of Green Coverage Ratio. Source: Prepared by the authors.

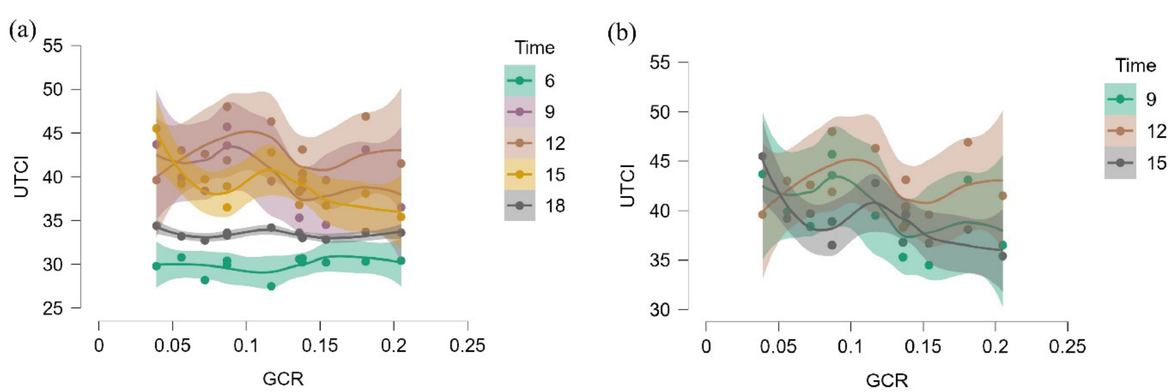

Figure 8. Time series data of the neighborhood (a) 6 am to 6 pm, (b) 9 am to 3 pm. Source: Prepared by the authors.

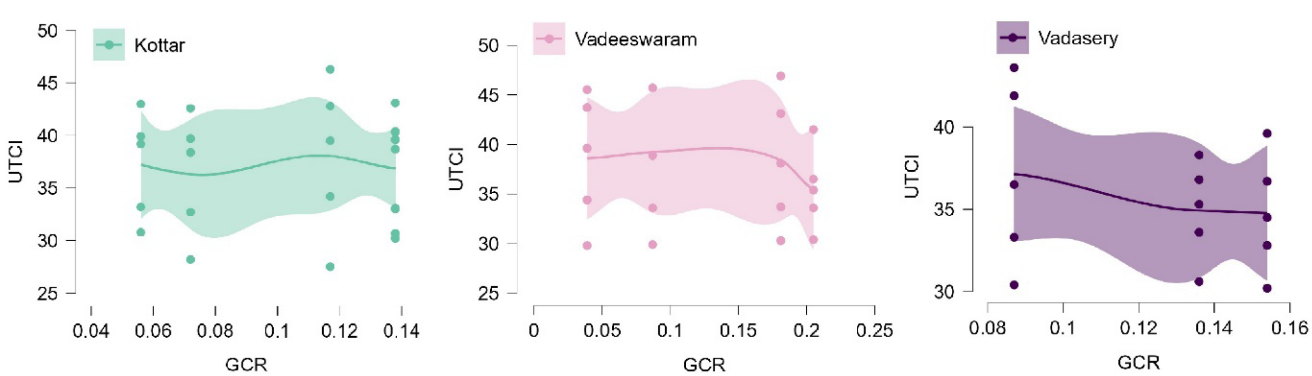

Figure 9. UTCI in the three neighborhoods N-1 - Kottar, N-2 - Vadeeswaram and N-3 – Vadasery. Source: Prepared by the authors.

similar maximums and minimums. While at 3 pm, the reduction was delayed with an increase in GCR. This suggests heat retention in areas with higher vegetation. The decrease in temperature is most prominent in N-3 (Figure 9). Hence, the vegetation in the street canyon led to a reduction in UTCI and significantly improved the thermal environment due to shading. However, a correlation between GCR and UTCI was not established.

BUILDING COVER RATIO

The relation between BCR and UTCI was analyzed. The analysis did not include the 6 am and 6 pm data, as no significant trend existed (Figure 10a). The increase in UTCI with an increase in BCR was established in Figure 10(b). The UTCI was normally distributed. Hence, a Pearson's r correlation was conducted on the data collected between 9 am and 3 pm. The value of Pearson's r was 0.422, with

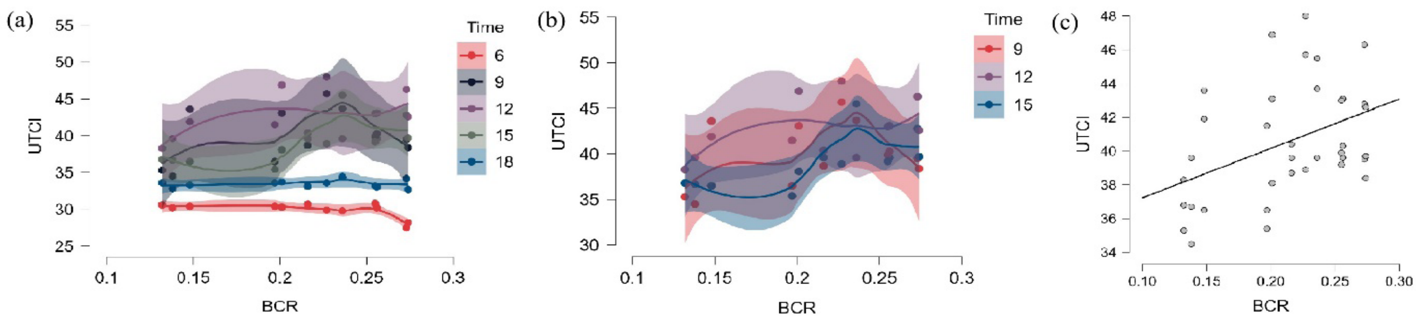

Figure 10. Time series data and correlation between BCR and UTCI. Source: Prepared by the authors.

a p-value of 0.010. Thus, BCR and UTCI have a positive relation of 17.8% and can reject the null hypothesis at a 5 % significance level. Thus, an increased fraction of the built environment will deteriorate the daytime thermal environment. Even though BCR, GCR, and OSR are three segments of a whole. The BCR established a significant correlation with the UTCI rather than the GCR (Figure 10c).

CONCLUSION

The neighborhood geometry was analyzed to address the summer heat stress in Kanyakumari. The influence of aspect ratio, sky view factor, green cover ratio, and building cover ratio on the Universal Thermal Climate Index was established. An increase in aspect ratio increases comfort during daytime, as observed in a similar study conducted in tropical cities (De & Mukherjee, 2018; Sharmin et al., 2019; Jamei et al., 2020). This case was valid in the absence of vegetation. However, vegetation in the neighborhood had an inverse effect on thermal comfort. An increase in aspect ratio decreased the thermal comfort when the street canyon had vegetation. This aligns with the study conducted in the coastal area of Sri Lanka (Emmanuel & Johansson, 2006). Moreover, a reduction in wind movement was observed when vegetation was introduced. Hence, a study suggested vegetation should not hinder wind movement to provide shade (S. Chen et al., 2020). The sky view factor had a positive relationship with the comfort variable. An increase in SVF led to an increase in daytime temperature variables. This aligns with the study conducted in similar climatic conditions (Sharmin et al., 2019; Yu et al., 2020). The ameliorating effect of vegetation was established as the shading effect of vegetation played a significant role in attaining comfort, similar to other studies (Johansson et al., 2004; Sun, 2011). An increase in building coverage reduces thermal comfort. Hence, a similar study recommended sparsely spaced tall buildings (De & Mukherjee, 2018).

This study attempted to understand the thermal interaction between 2D and 3D morphology and the surrounding environment in Kanyakumari. The study intended to reduce heat stress experienced by a coastal city in a tropical climate. Finally, shading was found to be a significant contributor to attaining thermal comfort. A higher aspect ratio and GCR, as well as lower SVF and BCR, were found to be ideal for developing a sustainable neighborhood. Additionally, the impact is reversed when vegetation is introduced into the morphology. Hence, lower aspect ratios are recommended when trees are introduced in the street canyon. In this study, the effect of orientation was not analyzed. Also, the influence of anthropogenic heat was avoided. Hence, future studies should address the impact of orientation and anthropogenic heat.

AUTHOR CONTRIBUTION CRediT

Conceptualization, M.S.; Data Curation, M.S.; Formal Analysis, M.S.; Funding Acquisition; Research, M.S.; Methodology, M.S. and A.M.S.; Project Management, A.M.S.; Resources, M.S.; Software. M.S.; Supervision, A.M.S.; Validation, M.S.; Visualization, M.S.; Writing-original draft, M.S.; Writing-review and editing; Writing-revision and editing, A.M.S.

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