International Journal of Biometeorology (2025) 69:245–260
https://doi.org/10.1007/s00484-024-02809-z

ORIGINAL PAPER

Quantifying the potential of evidence-based planting-pattern for reducing the outdoor thermal stress from a bio-meteorological perspective in tropical conditions of Indian cities

Saurabh Kishore Ojha[1] · Mahua Mukherjee[1] · Ar. Richa Raje[2]

Received: 6 May 2024 / Revised: 15 October 2024 / Accepted: 17 October 2024 / Published online: 24 October 2024

Abstract
The impact of declined natural greenery and increased built surfaces exacerbates heat stress in urban areas causing limited usage of outdoor spaces. Greenery strategies such as trees are capable of mitigating outdoor thermal stress gain because of their phytological properties. While urban greenery guidelines have suggested the ad-hoc procedure of tree planting-schemes based on aesthetic-value, soil-water preservation etc., understanding of their morphological character help in regulating extreme thermal condition. Hence, this study aims to investigate the most efficient planting pattern based on canopies densities and trees clusters for reducing the outdoor thermal stress from bio-meteorological perspective.

It initiates with the measurement of the site's morphological and meteorological attributes in existing commercial market of Bhopal City which has a humid sub-tropical climate (Aw, Koppen climate categorization). Furthermore, it leads to the development of 4-different iterated clusters incorporating moderate to high-density canopies and their overlaps pattern to estimate reduction potential in outdoors using field surveys and validated simulation model. The reduction potential in terms of magnitude and duration of thermal stress is quantified across 3-thermal variables i.e., air temperature, mean radiant temperature and universal thermal climate index. Results indicate highly-dense canopies are more effective in reducing greater magnitude of thermal stress along longer duration. Also overlapped planting pattern within the same canopy density does not make significant difference in stress reduction as compared to the changing the densities. This study will help planners and landscape architects to adopt evidence-based planting-pattern strategies for improving outdoor microclimate.

Keywords Canopy-density · Climate-suitable planting-pattern · Envi-Met simulation · Outdoor thermal stress · Optimizing trees thermal performance

Introduction

Cities are becoming warmer than their surrounding neighbourhoods due to the impact of rapid urbanization on the urban climate (Kotharkar et al. 2021). The impact of declined natural greenery and increased built surfaces exacerbates heat stress conditions in outdoor spaces causing human health risk (Akbari and Kolokotsa 2016). Consequently, there is urgent need to advocate evidence-based mitigation of outdoor thermal stress from an environmental quality perspective.

✉ Saurabh Kishore Ojha
skishoreojha@ar.iitr.ac.in

Mahua Mukherjee
mahuafap@iitr.ac.in

Ar. Richa Raje
richa.raje@spabhopal.ac.in

[1] Department of Architecture and Planning, Indian Institute of Technology, Roorkee, India

[2] Department of Landscape Architecture, School of Planning and Architecture, Bhopal, India

Implementing Urban greenery measures (UGM) for reducing the outdoor thermal stress

While developing a climate suitable urban design is a meticulous procedure that able to configure outdoor settings as an integral part of development plans, it is difficult to improve outdoor thermal condition in the heterogenous character of typical Indian cities, (Emmanuel 2021), (Ojha et al. 2022). Hence, the most practical method of enhancing the outside surroundings is to add greenery measures irrespective of its present condition. The benefits of implementing urban greenery measures are multifaceted, and they are associated to different shapes and scales such as urban parks (small scale to large scale), building level (terrace gardens to green façade) and street trees (Wang and Banzhaf 2018), (Ojha and Mukherjee 2022). Consequently, the significance of above researches focuses on implementing the urban greenery in different urban settings, as it positively influences the thermal comfort at pedestrian level.

Several long and short-term benefits for urban development plans are promoted by using trees as stress mitigation measures. Time-based interventions such as tree shade in exposed outdoors have a short-term impact and can only last a few heat-related events, while long-term options that can ameliorate the extremes of multiple heat-related seasons involve improving city green cover and water retention (GSDMA-HAP India 2022).

Quantifying the potential of evidence-based planting design and tree configuration

According to research, urban tree plantations generally are vulnerable to extreme climatic occurrences, such as heat stress, droughts, high winds, and pests (Hitchmough 2019). A study on the selection of trees suggests that it can be performed by modeling future climate conditions and then identifying species that are adapted to the climate for a resilient neighborhood (McPherson et al. 2018). The environmental benefits of trees in reducing heat stress can be extracted in a variety of strategies using theories and design guidelines, although a scientific analysis of the climatic suitability of the tree selection process is essential.

The climate impact of trees can be quantified using a variety of approaches, which is crucial for the selection process. One of the established method is to compute the amount of incident solar radiation that remains during the day after being immediately shaded by a tree canopy, while another method is to compute the amount of incident radiation that is converted into latent heat through transpiration (Dimoudi and Nikolopoulou 2003), (Moss et al. 2018). A tree's ability to control the surrounding environment is influenced by its morphological characteristics of tree species, which include trunk height, total height, total leaf area, and canopy shape (density/height/width).

The introduction of the current urban greenery guidelines, (The Manual of Planting & Landscaping of Urban-roads, Indian Road Congress 2018) and (Guidelines on Landscaping & Tree Plantation, Indian Road Congress 2009), should be taken into consideration before any proposals for greenery development are submitted. The aforementioned codes' key objectives are to reduce pollution, preserve water, prevent soil erosion, counter climate change, and enhance the aesthetic value (IRC: SP119 2018). Unfortunately, it neglects the quantitative analysis of thermal deviation generated by various kinds of trees species and planting schemes. Potential of reducing the thermal stress is usually quantified by the difference between the proposed iterations with the base case. However, the average values could underestimate the potential of effective distribution and duration of thermal stress reduction. There are several ways to present the potential of reducing thermal stress in numerical simulation models such as showing the distributions of quantified values by boxplot and mapping the delta value (temperature differences between iterated scenarios and base case) of thermal stress indicators with the help of Envi-Met simulation (Saeid et al. 2020). Thus, research into the interactions between a wide variety of tree species and planting techniques on microclimate is imperative.

Impact of canopy density and leaf area index

The potential of reducing outdoor stress with the help of trees can be observed through the process of shade and evapotranspiration, however shade becomes more significant as it distinguishes tree from other types of vegetation that lack shade (Ojha and Mukherjee 2024a, b). Trees' thermal performance, particularly in urban settings, is determined by their dimensions and concentration of their canopy, in along with the characteristics of their leaves (Ali and Patnaik 2018). The leaf area index (LAI), among other morphological attributes of various trees, is thought to be a key factor influencing incoming solar radiation and the thermal environment within the canopy, (Morakinyo and Lam 2016). The shading produced by trees with a broad canopy and a high leaf index and branch density is more efficient, (Monteiro et al. 2019). Trees species with a higher canopy density and LAI are preferred over those with a lower canopy density due to greater potential of reducing air temperature in respect to the three mitigation methods under consideration (shading, solar radiation reflection, and transpiration), (Zhang et al. 2022). In 2024, urban researchers on quantitative assessment of how various tree planting pattern and LAI affect the street thermal environment reported that the leaf area index LAI has significant impact on cooling of thermal environment, (Sachini J et al. 2024). It can be concluded that the potential of stress mitigation of urban trees depends primarily on the tree canopy and leaf characteristics LAI which plays an important role in tropical climates of Indian cities. Thus, it would be worthwhile to determine the most efficient morphological attributes of a tree needed for enhancing outdoor thermal conditions.

Investigating thermal stress indicators from a human bio-meteorological perspective

Many studies have demonstrated the beneficial effects of planting trees, though only a few of them have examined how thermal stress could be mitigated in terms of stress area rendered and stress duration by adapting a bio-meteorological perspective, (Yang.W et al. 2018), (Morakinyo 2019), (Ojha and Mukherjee 2024a). An investigation of urban trees reveals in detail how empirical measurement of humidity and related air temperatures influenced the outdoor thermal environment; however, it totally underestimated the bio-metrological analysis of thermal stress conditions (Sachini et al. 2024). According to one of the studies, (Physiological Equivalent Temperature, PET) as thermal stress indicators for calculating the impact of tree canopy and its clusters is the best acceptable technique to decide the environment suitability of open spaces, (Xinyi Luo et al. 2024).

Thus, in order to effectively express the outdoor thermal stress at pedestrian level from a human bio-metrology perspective, it is essential to compare the thermal stress across different thermal variables such as outside air temperature (Ta), mean radiant temperature, (MRT) and universal thermal climate Index (UTCI) for complete understanding (Sajad et al. 2018).

The relationship between meteorological factors like air temperature (Ta), globe temperature (Tg), wind speed (Ws), and indications like mean radiant temperature (MRT) is examined using Eq. (1) in order to study outdoor thermal stress, (ASHRAE 2017). In this case, global emissivity is represented by ε, and global diameter by D. In addition to these measurement techniques, the Envi-Met models are capable of simulating it.

$$\mathrm{MRT} = \left[(\mathrm{Tg}+273.15)^4 + (1.1*10^8*\mathrm{V}^{0.6}/\varepsilon*\mathrm{D}^{0.4})*\ (\mathrm{Tg}-\mathrm{Ta})\right]^{0.25} - [273.15] \quad (1)$$

However, in addition to the above three (Ta, Tg, and Ws), other meteorological elements such as relative humidity (Rh) and sun radiation (SR) are also included when assessing outdoor thermal stress when employing specialized field monitoring instruments. The rational indices like "physiological equivalent temperature" (PET) and "universal thermal climate Index" (UTCI) are generated from the heat budget equation for human-body with the help of advanced computational techniques (Mayer and Hoppe 1987). Therefore, it is essential to create a rational analysis that illustrates the effectiveness in terms of stress area rendered and stress duration.

Upon reviewing the outdoor thermal stress related studies, it has revealed following gaps:

(i) While urban greenery guidelines have suggested the ad-hoc procedure of tree planting schemes based on aesthetic value, soil & water preservation etc., while it neglected the thermal climatic impact of various kinds of tree configurations. Therefore, it would be worthwhile to investigate the compatibility of urban greenery guidelines to develop evidence-based planting design.

(II). Previous studies have used empirical indicators for examining the impacts of outdoor tree on thermal stress which is based on the combination of Ta and Rh. However, there is very few justifications on using rational indicators like UTCI, which offer a quantitative assessment of stress situation from a human bio-metrological perspective.

(iii). Previous research has focused exclusively on the influence of placement of vegetation (trees numbers) under uniform urban conditions. While this research makes an important contribution to the existing literature, proposing the most efficient planting pattern to estimate reduction potential of thermal stress using field surveys and validated simulation model.

Aim and objective

The research makes a significant contribution to the existing literature on thermal stress reduction in tropical conditions, providing quantitative analysis of rational thermal indicators and the environmental benefits associated with urban greenery. This study aims to investigate the most efficient planting pattern based on canopies densities and trees clusters for reducing the outdoor thermal stress from bio-meteorological perspective. The initial attempt is to explore climate suitability of available urban greenery guidelines suitable for pedestrian comfort in the Indian setting through literature. Further, the selected site can be compared with regard to morphological attributes such as orientation and aspect ratio.

Current research investigates outdoor thermal discomfort in a non-uniform condition taking into account:

I). To investigate the compatibility of urban greenery guidelines suitable for implementing evidence-based planting design which further helps to classify the selected site according to its morphological and metrological attributes.

(ii). To quantify the stress reduction potential of various iterations by adapting rational indicators such as Universal Thermal Climate Index (UTCI) from a human bio-metrological perspective.

(iii). To propose the most efficient planting pattern based on canopies densities and trees clusters to the extent they can be integrated and methodically analysing its impacts on outdoor heat stress in terms of stress intensity and duration rendered.

This research utilizes Envi-Met model for simulating the thermal climatic surroundings and urban microclimatic modelling. Further, implementing an evidence based integrated approach, the study combines Physical site survey followed by field measurements and numerical simulations to quantify the outdoor thermal stress.

Methodology

The morphological and metrological attributes affecting the thermal conditions in the study area were quantified using numerical simulation modelled in Envi-Met. Assessments of microclimatic components includes physical measurements in terms of outside air temperature (Ta) and relative humidity (Rh). This model has been verified as well employing field measurements gathered during a site survey. The study concludes by analysing simulation findings using comparative analysis and identifying most effective planting design for stress mitigation Fig. 1.

Study area characterization

The study area is located in Bhopal, capital city of Madya Pradesh in India (23.27° N, 77.33° E) with humid sub-tropical climate (Aw) according to the Koppen climate categorization. The maximum outside air temperature (Ta) range is 43 °C to 45 °C during summer and minimum temperature reaches 7.5 °C to 8.5 °C during peak winter season while the annual average wind movement in selected city remains 3.15 m/s with maximum goes up to 8.5 m/s. The annual variation in average relative-humidity (Rh) is 65%.

This investigation surveyed the open ground in Bhopal City's commercial area. The area mostly consists of eating places, market stalls, and shopping centres. The physical survey followed by on site measurement was done at the mark point according to the microscale study criteria of under 1 km, (T.R.Oke 2006). To incorporate the influence of buildings and site physical character we developed a block scale model of 200 m × 250 m. The site measurement was schedule to understand the microclimatic behaviour at selected outdoor area during extreme summer time.

The strategy of data collection is to collect the Ta and Rh for the period of 25-hours so that effect of one typical summer day can be captured. In accordance with on-site data, the numerical simulation experiment indicated that the geographic coordinates were (23.27° N, 77.33° E), whereas the modelling weather was average summer day without clouds. The field measurement was conducted during extreme summer time at a single observation point on a selected spot consecutively for 24-hours. The local time and date were fixed for May 25th from morning to next morning

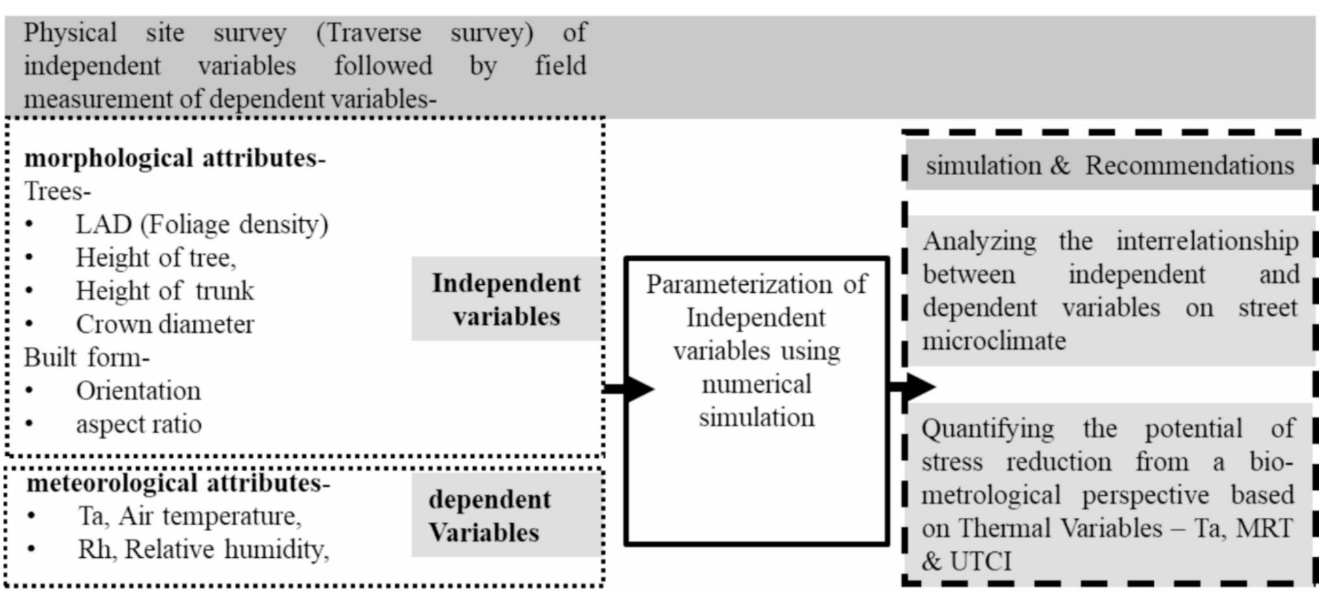

Fig. 1 Methodology stages

in order to guarantee that selected open areas were exposed to direct sunlight.

The field-measuring point marked in Fig. 2, demonstrate typical outdoor area located at extreme north edge of the plot. The device for on-site field measurement was installed in the middle of the predetermined spot at the height of 1.50-meters above the finish road-level. The experiment was intended to collect measured and simulated data on microclimate variables at a height of 1.50-meters above road/ground level in order to approach the “human-biometeorological reference height.” ((Mayer 1993). To facilitate the experiment, the Ta and Rh data was recorded at hourly intervals over a duration of 25-hour during the site survey the with the help of Data-logger Testo-174 H which further used for model validation, (Ojha and Mukherjee 2024b, Manavvi and Rajasekar 2021). The Data-logger Ta sensor had an accuracy of ±0.5 °C and a temperature range of -10 °C to +70 °C. The humidity ranges from 2 to 99% with an accuracy of ±3%., as shown in Table 1.

Simulation model setup

Envi-Met is capable of measuring the outdoor thermal stress of different iterations in terms of the duration and the area rendered with the stress in both spatial and temporal dimensions. A block scale model of 200 m x 250 m, representing site was simulated over the course of a 25-hours to quantify the impact of proposed iteration over existing scenario. Based on extreme stress period in summer a physical survey followed by field measurement was scheduled. The computed outcome was validated across micro-meteorological variables (Ta and Rh) collected physically on-site over the duration of 25-hours.

It should be noted that the threshold for calculating thermal stress across indicators (Ta, MRT, and UTCI) is

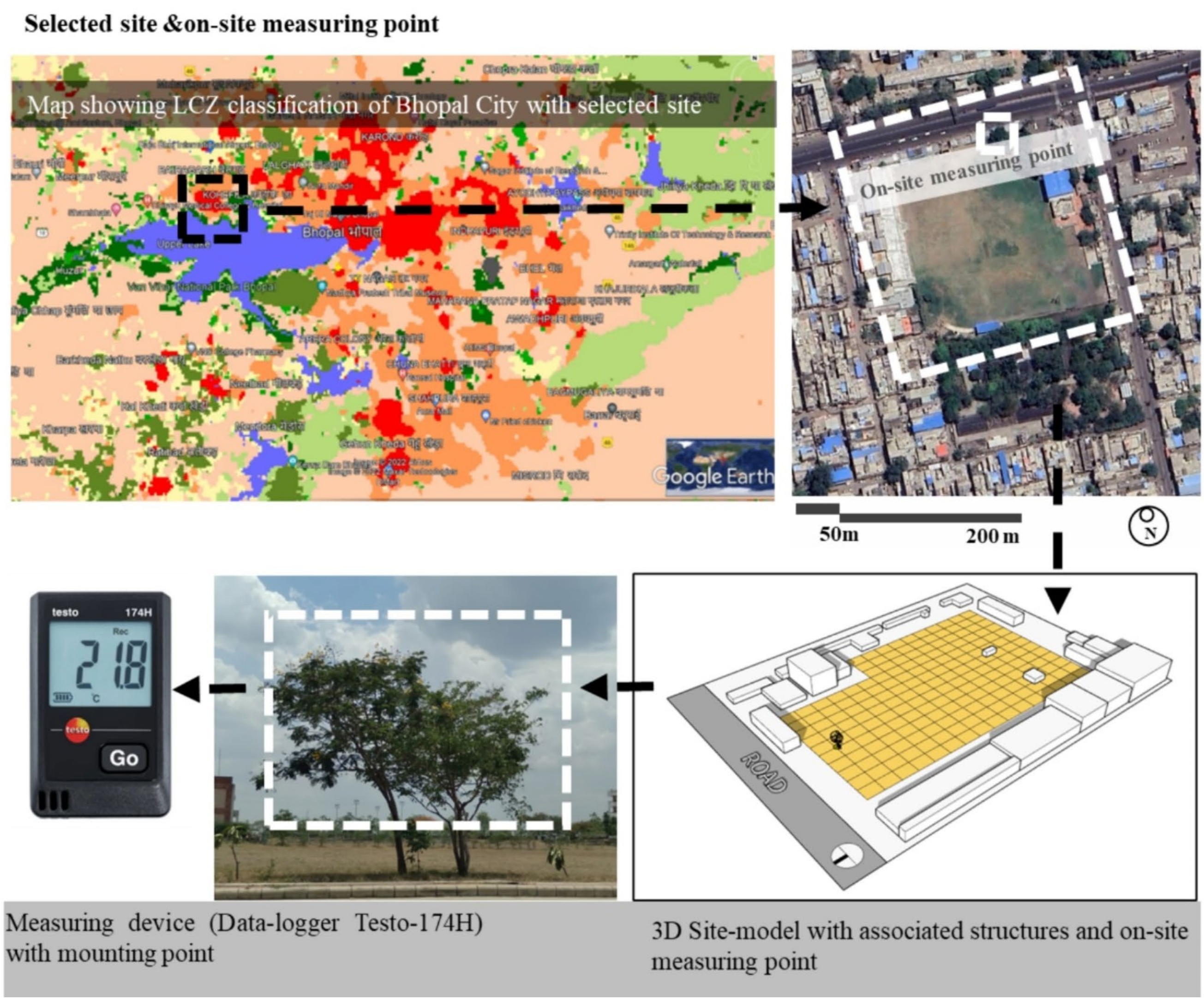

Fig. 2 LCZ classification of Bhopal City with selected site, adapted from (Wadwekar 2021) and on-site measuring points with monitoring device

Table 1 On-site measurement schedule

Monitoring device	Meteorological variables	Measuring range, accuracy and resolution	On-site measurement schedule
Data-logger Testo-174 H	Air temperature (Ta)	Measuring range: -20 °C to + 70 °C Accuracy: ±0.5 °C Resolution: 0.1 °C	Data collected from, 25-**05-2023**, morning 09:00 to **26-05-2023**, morning 09:00.
	Relative humidity (Rh)	Measuring range: 0 to 100%, Rh Accuracy: ±3% ±3% (2 to + 98%), ± 0.03% Resolution: 0.1%Rh	

commonly represented in degrees Celsius. Furthermore, indicator like UTCI analysed thermal stress output by representing negative and positive ranges of temperature in degrees Celsius that show comfortable or discomfortable thermal conditions. According to the Human Thermal Index (UTCI), "thermal comfort" means "no thermal stress" between 9 and 26 degrees Celsius. The relationship between threshold settings across indicators used in current study were based on the previous references and ISO standards such as ± 0.5°C for Ta (ASHARE 2022), ± 5°C ◦C for MRT (ISO 1985), and the UTCI change value for each thermal perception class was in the 3°C range, (Patle and Ghuge 2024). A prior study found that the thermal sensation ranges of Universal Thermal Climate Index (UTCI) are classified over a ten-point temperature scale ranging from highest heat stress and lowest cold stress (Jendritzky 2012).

The thermophysical interactions between urban regions are predicted using Computational Fluid Dynamics (CFD) simulations, such as Envi-Met. To predict the turbulence in the outdoor environment, these simulations employ two-equation Turbulence Kinetic Energy (TKE) models (ENVI-MET 2024). Data collection was conducted on clear, sunny days with almost cloudless skies. It is assumed that modelling bright days is more accurate than the Envi-Met model because it does not account for sky cloudiness, (Taleghani 2015).

The urban model, which depicts the current outdoor environment, was made inside a three-dimensional box with x, y, and z axes measurements of 5.0, 5.0, and 3.0 m, respectively. The x, y, and z axes have 40 grid numbers in x axis direction, 50 in y axis direction and the z axis has 30. In order to generate 3D models, it also permits the use of vertical grids; however, all of the grids, with the exception of the bottom five, have an equal vertical extension, (ENVI-MET-Knowledge Base Index 2024).

Evaluating the impacts across a whole day (24 h) was the reasoning behind choosing a 25-hour simulation. The variability of meteorological aspects on microclimate was observed for 25-hours duration starting at 25-05-2023, 09:00 AM to 26-05-2023, 09:00 AM. Thus, in order to faithfully replicate the entire day's events, the simulation model launched at 9 a.m. on day one and ended at 9 a.m. on next day, making a total of 25-hours of simulation.

The albedo and emissivity of solid surfaces, geometrical characteristics of buildings and plants, date and time, latitude and longitude, altitude, and time zone are all taken into account when simulating radiation fluxes in this model. The walls are made of hollow concrete blocks, and the flat roofs are reinforced concrete. The simulation used thermophysical property data from the Envi-Met default database for building materials. The model's database was also used to extract soil and surface information. These ground surface profiles were most frequently used: [0100ST] for asphalt roads, [0100PG] for concrete pavement, and [0100LO] for natural surfaces like loamy soil. The scenarios were created to show how the micro-metrological attributes at outdoors are influenced by the tree planting pattern and tree morphology (leaf area density). As shown in Fig. 2, the height of the surrounding buildings along the ground ranges from 2.0 m to 12.0 m while the building material for structure were all of various cement concrete grades such as M15 to M25. The Envi-Met 3D model demonstrating the surrounding building structure was proposed into a virtual assembly as shown in Table 2.

It takes the yearly climatic data into account in order to replicate the highest stress period of a typical summer day, (ISHARE 2022). According to ISHARE climatic database the maximum thermal stress was May with 900 to 1200-Watt hour/m² of average incident direct solar radiation and average temperature range of above 40 °C. Thus, the selected date for Envi-Met simulation considered was May 25th and a site-survey was completed to collect micro-meteorological variables for simulated model validation. It seems reasonable to demonstrate the simulated local wind speed, humidity, and air temperature in the afternoon (02:00 to 03:00 PM) which is the most thermally taxing time of day (Bhaskar & Mukherjee 2018).

To understand the current impact of typical planting strategies undertaken by Govt. of India for open space and road side plantation a comparative analysis was conducted. The strategy which includes type of tree based on canopy densities were taken from one of such guidelines provided by Forest Survey of India, (FSI). Three types of tree canopies, ranging from less than 40%, between 40% and 70%, and greater than 70%, were investigated in accordance with the Forest Survey of India's criteria, as shown in Fig. 3,

Table 2 Description of Envi-Met simulation boundary conditions

Simulation Input parameter	Details of input
Model domain	
Site-coordinates	(23.27° N, 77.33° E).
Simulation model & Domain size	$40 \times 50 \times 30$ grids and $\Delta x = 5\ m$, $\Delta y = 5\ m$ & $\Delta z = 3\ m$, (Δz of lowest grid box is split into 5 in vertical grid with the equidistant method).
Simulation day	2023.05.25 to 2023.05.26 (Summer season).
Simulation period	Morning 9:00, 25th May to Morning 9:00 26th May, for 25 h
Meteorological data	Hourly-data from extracted the measuring points during site visit.
Climate	humid sub-tropical climate (Aw) according to the Koppen climate categorization.
Air Temperature (Ta)	28.4 °C to 43.1 °C.
Relative Humidity (Rh)	18–52%
Wind Speed (Ws) & direction	3.15 m/s and 315°NW(North-west).
Time of max Ta and min Rh	15:00 in summer.
Time of min Ta and max Rh	04:00 in summer.
Plant and ground surface profile	Trees: 15-m moderate and highly dense with cylindrical shape canopy and ground surface profiles were most frequently used: [0100ST] for asphalt roads, [0100PG] for concrete pavement, and [0100LO] for natural surfaces like loamy soil.
Cloud cover	Zero.
Receptor height	1.5 m from Ground/road level.
Built-up structures features	Cement concrete grades M15 to M25 were used as the building material for the structure, and the walls and roofing had respective heat transmission values of 1.9 W/m2*K and 5.0 W/m2*K.

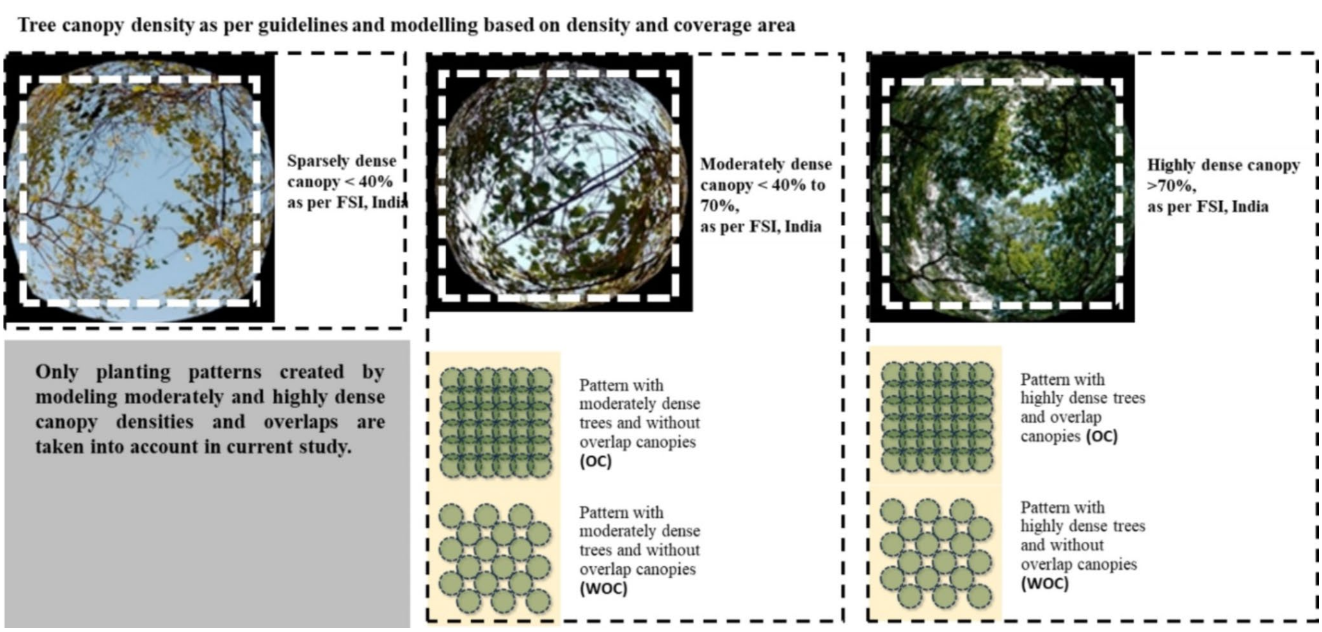

Fig. 3 Tree canopy density as per guidelines and planting pattern

where less than 40% represents sparsely foliated canopy density, 40–70% represents moderate density and greater than 70% shows highly dense canopy, (FSI 2015). After the vegetation was introduced to all of the simulations, the leaf area density (LAD) were selected as a representation of tree canopy density from the (Albero) Envi-Met model database. Albero database makes it possible to digitize intricate tree roots and crowns by employing cell clusters with different densities for the roots and leaves (Leaf Area Density and Root Area Density). Since the root morphology in this study had little bearing on the simulation results, the root morphology in the experiment was set to the software's default values (SimonH 2016). To ensure that any change in outdoor thermal discomfort was solely attributable to changes in tree topologies and morphology, all proposed simulations employed the same fundamental input parameters, with moderately foliated trees representing low LAD values (ranging 3 to 4) and densely foliated trees representing high LAD values (ranging 5 to 6).

The present study employed leaf area density values of 3 and 6 to characterize tree canopy densities computationally. A tree with a moderately dense canopy was modeled with a LAD 3.0 value, and a tree with an extremely dense canopy was computed with a LAD 6.0 value. The other physical attribues in the simulation was tree height of 15.0 m, cylindrical shape canopy of 12 m diameter, and a trunk of 3.0 m height from the ground level. As shown in Fig. 3, two configurations using continuous tree rows were suggested based on extent of canopy overlap for the planting design. The first pattern involved progressively arranging trees so that their canopies overlapped adjacent ones by more than 50%, whereas the second pattern involved sequentially arranging trees so that there was no canopy overlap at all.

Parametric study

To analyse the summer thermal stress five different iterations of planting pattern based on canopies densities and trees clusters were simulated on May 25th 2023. The selected ground without trees-oriented clock-wise 15° East-west from the north was considered as the base case. The first of the two categorization was borrowed from the previous study which is based on tree configuration and its impact on microclimate, (Morakinyo et al. 2017). As the first classification the clusters of trees with and without canopy overlaps had been the proposed planting iterations. The second classification is based on the canopy density (leaf area density, LAD), which ranged from 3 to 6 (moderately dense canopy and highly dense canopy). In conclusion, the simulations were carried out for base case in which there is no tree, hence no canopy and without any overlap canopies (NC-WOC), followed by moderately dense canopy and overlap canopies clusters (MDC-OC), moderately dense canopy and without overlap canopies clusters (MDC-WOC), highly dense canopy and overlap canopies clusters (HDC-OC), and lastly planting-pattern with highly dense canopy and without overlap canopies clusters (HDC-WOC), as shown in Table 3. To quantify the stress reduction potential of various iterations three thermal stress indicators were considered: air temperature (Ta), mean radiant temperature (MRT), Universal Thermal Climate Index (UTCI).

Results

Field data measurement and envi-met model validation

The primary challenges in developing a climate suitable outdoor area are recognizing the critical sets of magnitude and durations with the extreme thermal stress conditions. The higher aspect ratio building located at south-western edges results in a low intensity incoming radiation in late evening and night hours. The variability of air temperature (Ta) and humidity (Rh) on microclimate was observed during the field visit summer day on 25th May 2023. As shown in Fig. 4, the site-survey data was collected for 25-hours duration starting at 25-05-2023, morning 09:00 to 26-05-2023, morning 09:00.

The results indicate that there was a difference of almost 15 °C in the highest and lowest range of measured temperatures and a difference of 35% in the highest range of observed humidity. The afternoon hours of 14:00 to 15:00 were the highest temperature and humidity levels recorded, while the morning hours of 05:00 to 06:00 were the lowest and maximum temperatures, respectively. It is so evident that pedestrian users and vendors are directly getting affected by extreme diurnal changes in temperature, hence it is critical to investigate the broader implications of whole day variation on human health risk.

The data gathered by field measurements of air temperature (Ta) and humidity (Rh) has been verified considering the summer day 25th of May 2023. The observed maximum Ta, Rh and Ws range was 28.4 °C to 43.1 °C, 18–52%, 3.15 m/s from North-West respectively. The data (Ta and Rh) acquired during the field visit were used to validate the proposed simulation model. The results of the simulation were quantitatively analysed using the data from the designated monitoring point. The results are then examined after estimating the correlation coefficients (R Square) and root-mean-square error (RMSE). The scatter graph of observed and simulated air temperature (Ta) and relative humidity (Rh) between the collected field data and computed data on a typical stress duration from morning 09:00 AM, May 25th to next day morning 09:00 AM, May 26th 2023 is represented in Fig. 4. The value of R-square caluation varies from 0.95 for Ta and 0.83 for Rh, while air temperature (Ta) and realtive humidity (Rh) came up with RMSE value of

Table 3 Scenario development process by combining tree coverage area and canopy density

Scenario name	Proposed planting-pattern	LAD values
(NC-WOC)	base case without any density or overlap canopies.	LAD 0
(MDC-OC)	planting-pattern with moderately dense canopy and overlap canopies clusters.	LAD 3
(MDC-WOC)	planting-pattern with moderately dense canopy and without overlap canopies clusters.	LAD 3
(HDC-OC)	planting-pattern with highly dense canopy and overlap canopies clusters.	LAD 6
(HDC-WOC)	planting-pattern with highly dense canopy and without overlap canopies clusters.	LAD 6

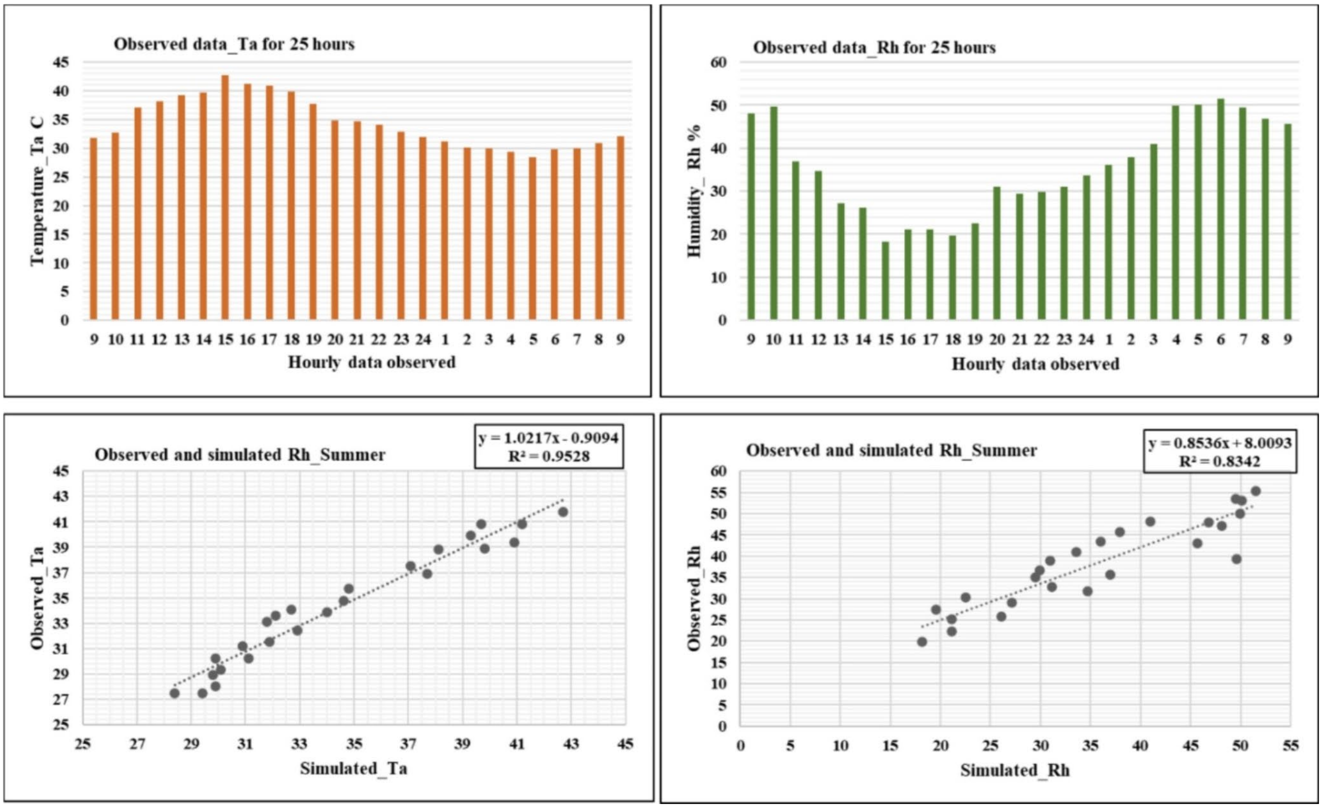

Fig. 4 (Top), Variation of measured (Ta) and (Rh) on-site for 25-(hours) duration during summer day, bottom: Simulated & measured results (Ta) and (Rh) during identified summer period

0.99 and 5.2 respectively, similar to previous reserch (Karimi 2020).

Performance of planting-pattern across the stress duration

This part evaluates the impact of different canopy densities on outdoor thermal stress in terms of magnitude and duration of thermal stress. The moderate dense canopy (MDC) showed maximum reduction of 0.91 °C to 1.71 °C for Ta, 22 °C to 25 °C for MRT & 11 °C to 12 °C for UTCI values, during morning hours while for afternoon the reduction was 2.2 °C to 3.1 °C for Ta, 28 °C to 32 °C for MRT & 5 °C to 6.5 °C for UTCI. This demonstrates that Ta behaves differently from MRT & UTCI, and that moderate dense canopies (MDC) have distinct impacts on all three thermal variables. It significantly lowers the Ta by up to 1.5 °C from morning to afternoon, but has minimal effect on the MRT (which decreases by 4 °C), The UTCI is lowered by 11 °C in the morning but only by 6 °C in the afternoon, indicating lower variation in the reduction of the UTCI from morning to afternoon. In conclusion, MDC is not significantly advantageous in reducing MRT and UTCI in extreme afternoon hours compared to the morning, though it exhibits a large reduction of Ta throughout the day. During evening hours (16:00), the variation trend was the same as in the afternoon, with a bigger drop of UTCI up to 10 °C, demonstrating that density does not impact the UTCI in the presence of direct incident radiation when the Sun azimuth angle is high to the observer point.

Later, during the evening and night, a moderate tendency contrary the one mentioned above has been noted. The Ta only exhibited a slight change (down 0.35 °C), whereas the reductions in MRT and UTCI were up to 4.5 °C and 2 °C, respectively. However, during the late-night hours, there was a slight spike in distress (MRT & UTCI rises by an average of 9 °C and 5 °C respectively), because of the raised MRT and UTCI fluctuation, due to limited wind movement between tree canopies. Figure 5.

During the morning, the extremely dense canopy (HDC) showed a maximum reduction of 1.5 °C to 2.3 °C for Ta, 29 °C to 32 °C for MRT, and 14 °C to 16 °C for UTCI, while the afternoon drop was 2.3 °C to 4.0 °C for Ta, 32 °C to 37 °C for MRT, and 9 °C to 11 °C for UTCI. Evenings see an even greater performance from the HDC, with average of Ta dropping to 3.8 °C, MRT to 32 °C, and UTCI to 13.5 °C. Consequently, HDC improves the microclimate by lowering a wider range of UTCI than MDC. In contrast to the MDC, the HDC lowers Ta by 0.5 °C, MRT by 5 °C, and UTCI by 4 °C in the morning, and lowers Ta by 0.1 °C

MDC												
	MDC_OC						MDC_WOC					
TIME	MDC_OC_NORTH EDGE			MDC_OC_SOUTH EDGE			MDC_WOC_NORTH EDGE			MDC_WOC_SOUTH EDGE		
	TA	MRT	UTCI	TA	MRT	UTCI	TA	MRT	UTCI	TA	MRT	UTCI
MORNING 06	0.03	-1.5	-0.3	0.5	-1.5	-0.3	0.03	-1.2	-0.75	0.5	-1.2	-0.5
MORNING 08	-0.9	-25	-15	-1.2	-25	-15	-0.7	-26	-14	-1.3	-26	-14
MORNING 10	-1.1	-25	-11.4	-1.9	-25	-11.8	-0.9	-22	-10.9	-1.7	-22	-10.9
AFTERNOON 12	-2.4	-26	-9.1	-4.8	-26	-8.4	-1.4	-22	-7.5	-3.8	-22	-7.2
AFTERNOON 14	-2.2	-32	-5.8	-3.6	-32	-5.4	-1.4	-28	-5.4	-3.1	-28	-4.9
EVENING 16	-1.7	-31	-8.5	-3.4	-31	-9.1	-1.8	-29	-7.2	-3.2	-29	-7.2
EVENING 18	-0.35	-1.5	1.6	-0.35	-1.5	1.6	-0.2	-1	2.1	-0.2	-1	2.1
EVENING 20	-0.05	4	3.5	0.5	4	3.5	0.35	5	3.6	0.35	5	4
NIGHT 22	0.1	8	3.8	04	8	3.8	0.4	8	4.5	0.5	8	2.9
NIGHT 24	0.1	8.5	3.5	0.4	8.5	3.5	0.5	8.5	3	0.3	8.5	3.6
NIGHT 02	0.2	9	5.7	0.3	9	5.1	0.5	6	5.2	0.3	6	6
NIGHT 04	0.2	8	5.5	0.3	8	5.5	0.5	6	5.2	0.3	6	5.7

HDC												
	HDC_OC						HDC_WOC					
TIME	HDC_OC_NORTH EDGE			HDC_OC_SOUTH EDGE			HDC_WOC_NORTH EDGE			HDC_WOC_SOUTH EDGE		
	TA	MRT	UTCI	TA	MRT	UTCI	TA	MRT	UTCI	TA	MRT	UTCI
MORNING 06	-0.4	-4.8	-1.7	0.2	-4.8	-0.9	-0.1	-2.5	-0.9	0.2	-2.5	-0.5
MORNING 08	-0.9	-25.8	-13.5	-1.2	-25.8	-16	-0.4	-26	-14	-0.7	-26	-14
MORNING 10	-1.5	-31.2	-16	-2.3	-31.2	-16	-1.5	-29	-14	-2.1	-29	-14
AFTERNOON 12	-2.6	-31.8	-13	-4.8	-31.8	-15	-1.7	-29	-11	-3.5	-29	-11
AFTERNOON 14	-2.2	-37.5	-11.1	-4.0	-37.5	-11.1	-1.5	-34	-9	-3	-34	-9
EVENING 16	-2.8	-35.3	-13.2	-4.2	-35.3	-12.8	-1.5	-32	-9.5	-3	-32	-9.5
EVENING 18	-1.5	-1.8	-2.2	-2	-1.8	-3.4	-0.7	-1	-1.5	-1.4	-1	-2.2
EVENING 20	-0.75	5	-0.2	-1.2	5	-5	-0.3	4.5	0.5	-0.6	4.5	0.2
NIGHT 22	-0.8	8.5	1.2	-0.6	8.5	1.5	-0.4	8	1.5	-0.1	8	1.7
NIGHT 24	-0.5	9.2	2.5	0.07	9.2	3.2	-0.2	6	2.8	0.1	6	4
NIGHT 02	-0.1	9.2	3.2	0.2	9.2	4.7	-0.2	7.5	4	0.3	7.5	4.5
NIGHT 04	-0.2	9.2	2.4	-0.2	9.2	3.7	0.1	6	2.5	0.5	6	4.5

Fig. 5 Impact of canopy density (MDC & HDC) and trees numbers across thermal variables

to 0.9 °C, MRT by 5 °C, and UTCI by 5 °C in the afternoon. Therefore, it is evident that canopy density is directly proportional to temperature reduction in all three variables. Also, highly dense canopies contribute to a more consistently maintained UTCI value over a longer period of time, like morning (10:00) until evening (16:00). Finally, employing HDC improved the temperature reduction ability for all three variables throughout working hours likewise, HDC reduces MRT and UTCI for 50% longer duration and with a 20% greater magnitude.

Variability of thermal stress (Ta, MRT, UTCI) across different planting pattern

The following part examines how planting patterns based on tree clusters with varying degrees of canopy overlap affect thermal variables. According to the outcome for summer time, the thermal variation of north edge and south edge of the ground shifted during the morning time leading to enhance thermal-climate condition. The temperature difference across all thermal variables in morning showed minimum variations between the south and north edges. Its afternoon the Ta 1.2°C difference was notable between both the edges irrespective of canopy overlap or canopy density.

Thermal stress was calculated as the temperature difference (delta k) between all proposed planting pattern and the reference scenarios. The results demonstrate coloured spatial distribution, computed in Envi-Met simulation. Greater and negative delta readings correspond to temperature reductions from the base scenario, and vice versa, as shown in Table 4.

Air temperature, Ta was consistently lower in all iterated planting scenarios compared to the base case. Planting high density canopy with overlap clusters (HDC_OC), achieved the best reduction potential across all iterations (MDC-OC), (MDC-WOC), (HDC-OC) & (HDC-WOC) resulting in reductions of 2.2°C, 1.4 °C, 2.3 °C, and 1.6 °C in Ta at 14:00, respectively. The highest air temperature (Ta) reduction was attained for alternatives with the highly dense canopy with overlap clusters (HDC_OC), eventually followed by a relatively reduced values for moderate dense canopy with overlap clusters (MDC_OC). The reduction potential

Table 4 Calculation for analysing the influence of different planting pattern across thermal variables (Ta, MRT & UTCI)

Thermal variables	Details of scenarios calculated	Input calculations
Air temperature (Ta)	Moderate density canopy with overlap canopy pattern.	ΔTA = TA (MDC_OC)- TA (BC)
	Moderate density canopy without overlaps canopy pattern.	ΔTA = TA (MDC_WOC)- TA (BC)
	Highly density canopy with overlap canopy pattern.	ΔTA = TA (HDC_OC)- TA (BC)
	Highly density canopy without overlaps canopy pattern.	ΔTA = TA (HDC_WOC)- TA (BC)
Mean Radiant temperature (MRT)	Moderate density canopy with overlap canopy pattern.	ΔMRT = MRT (MDC_OC)- MRT (BC)
	Moderate density canopy without overlaps canopy pattern.	ΔMRT = MRT (MDC_WOC)- MRT (BC)
	Highly density canopy with overlap canopy pattern.	ΔMRT = MRT (HDC_OC)- MRT (BC)
	Highly density canopy without overlaps canopy pattern.	ΔMRT = MRT (HDC_WOC)- MRT (BC)
Universal thermal climate index (UTCI)	Moderate density canopy with overlap canopy pattern.	ΔUTCI = UTCI (MDC_OC)- UTCI (BC)
	Moderate density canopy without overlaps canopy pattern.	ΔUTCI = UTCI (MDC_WOC)- UTCI (BC)
	Highly density canopy with overlap canopy pattern.	ΔUTCI = UTCI (HDC_OC)- UTCI (BC)
	Highly density canopy without overlaps canopy pattern.	ΔUTCI = UTCI (HDC_WOC)- UTCI (BC)

of moderate canopy without overlap clusters was the least effective, reducing Ta by only 1.4℃. However, in without overlap canopy pattern (WOC), both canopy density (MDC & HDC) demonstrated decreased ability to reduce Ta in afternoon and evening. While the reduction was the least pronounced, both leading to lesser reduction of 0.7℃ to 1.5℃ in Ta than their overlap pattern (OC).

Throughout the entire 24 h simulation, with the exception of night time (22:00) to late night time (24:00), mean radiant temperature, MRT in all scenarios remained lower than that in base case. In overlap canopy clusters (OC), high density (HDC) demonstrated a more pronounced cooling effect at morning 10:00 to evening 16:00, resulting in a considerable reduction by 31℃ to 37℃ respectively. At evening, it displayed the least effective reduction potential, reducing to decrease in MRT of 5℃. Conversely, all iterated scenarios displayed the negative impact in reducing MRT during night-time, with a maximum expansion of 9℃, resulting in an average increase of 4℃. This phenomenon could be explained by the fact that the trees canopy notably restricts local wind movement and it could make situation worst if the highly dense canopy is clustered closed to each other in an overlapped canopies pattern. The major benefit of using HDC over MDC is that it reduces MRT significantly i.e. up to 8℃ during the peak discomfort period i.e., in afternoon. During the evening (18:00 to 20:00) time the fluctuations are very little in all iterated scenarios ranging less than 4℃ change in MRT. While, in night time after 22:00 the overall results for MRT were in accordance with Ta, indicating that various canopy densities did exhibit similar variations in reducing MRT by 7℃ to 8℃ from base scenario in case of implementing either of them (MDC & HDC). This could be attributed to the impact of trapped long wave radiation at pedestrian level, within the canopy densities of the tree's clusters.

The experiment outcomes indicated a similar trend between MRT & UTCI, suggesting that UTCI is significantly affected by day time solar radiation. From morning (10:00) to evening (16:00), the UTCI values on spots across all iterations was lesser than that for base case. Although the UTCI ranges of all MDC iterations fell within the extreme thermal stress zone in afternoon, regardless of the existence of trees. This finding highlighted the limited reduction potential of developing trees clusters without overleaped planting pattern in outdoor areas in extreme heat conditions. According to the Fig. 6, the WOC clusters of both moderate and high density (MDC & HDC) shows 1.4℃ & 2℃ more UTCI in afternoon than that of OC clusters. Furthermore, at both densities (MDC & HDC), the UTCI ranges of WOC were consistently larger than OC. This helps to explain why a dense planting pattern with overlapped canopies clusters restricts direct sun radiation consequently reduces UTCI.

Between the tree canopy densities HDC displayed the highest reduction in OC & WOC, reducing the UTCI by 13.5 °C & 9.5 °C, at evening 16:00, respectively, while MDC indicated the lowest degree of reduction on the UTCI, lowering it by 9.1℃ and 7.2℃ at 16:00 h, respectively. The sequence in which distinct tree canopy types have cooling effects on the UTCI, from greatest to least, was: HDC_OC > HDC_WOC > MDC_OC > MDC_WOC. It is interesting to know that HDC_WOC and MDC_OC shows the almost similar value of UTCI, which establish the fact that sparse arrangement of highly dense canopies gives same comfort of dense arrangement of sparse canopies. Nevertheless, the simulation results clearly demonstrated that overlapped planting pattern within the same canopy density does not make significant difference in Ta reduction as compared to the changing the densities.

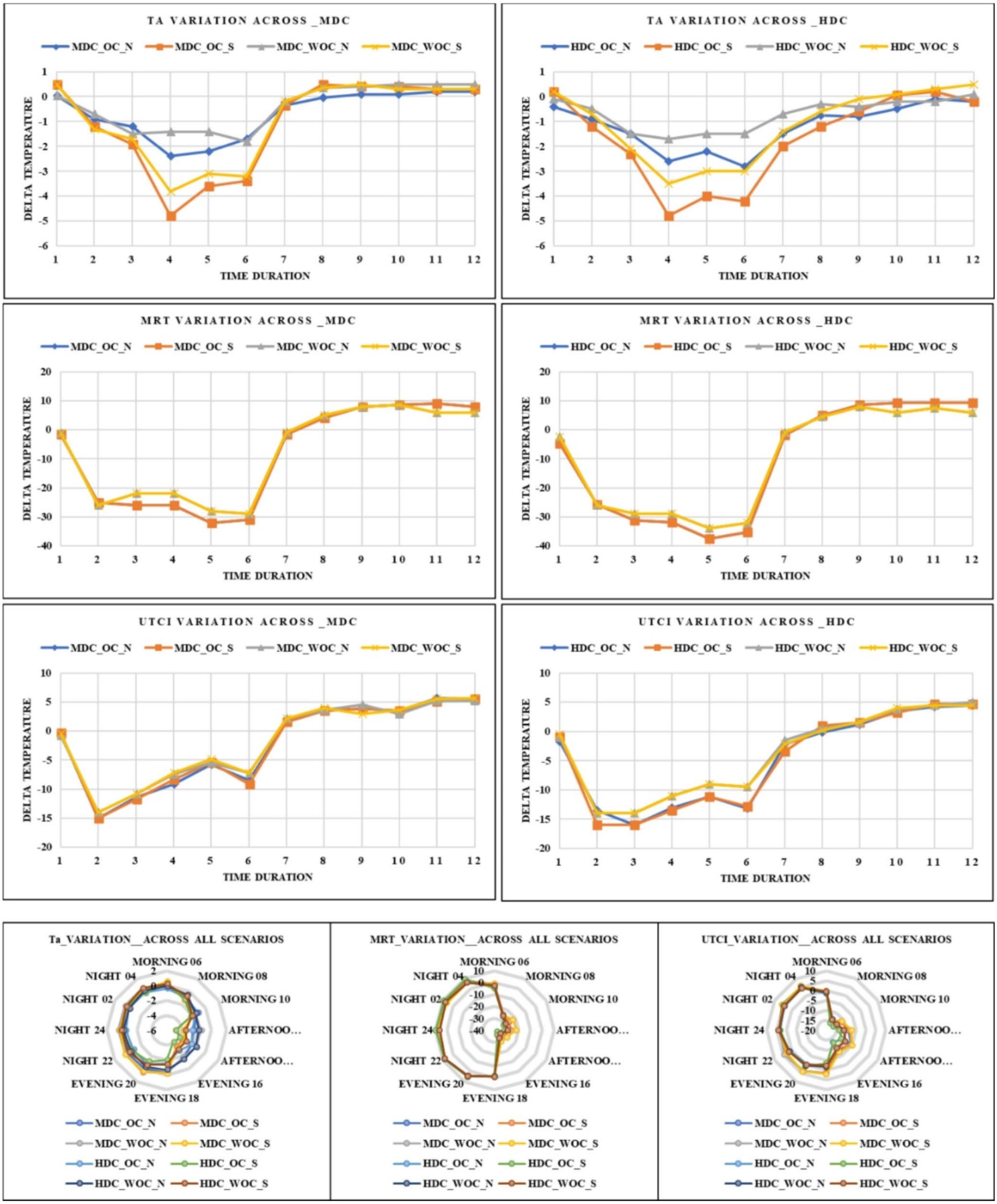

Fig. 6 Potential of discomfort mitigation across thermal variables Ta, MRT & UTCI

Disscussion

The research being conducted focused on the premise of planting pattern and canopy density of the tree's clusters in urban outdoor area. Consequently, the finding of each cluster and densities had its own impact on effectively reducing thermal stress across all three variables Ta, MRT & UTCI. These findings were consistent with of previous research supporting similar outcomes with outdoor tree planting (Ojha and Mukherjee 2024a, b). The lower Ta and higher reduction potential reached in Overlapping canopies pattern can be connected to the minimal radiation exposure of the below-canopy area (Makaremi et al. 2012). Simulated air temperature results with dense tree crowns and overlapping canopies reveal that tree evapotranspiration reduces temperature, resulting in stress mitigation (Srivanit and HokaoK 2013). Climate amelioration is one of the primary objectives of the urban greenery guidelines. Thus, current experiment makes advantage of the possibility of evidence-based tree plant selection and planting design, which can be employed as a decision-making tool for urban greenery proposals (IRC021 India 2009).

Variation in thermal stress mitigation by planting pattern

The analysis also showed that high density canopies (HDS) and moderate density canopies (MDC) of overlap canopy clusters (OC) were cooler during the day time than HDS & MDS of without overlap canopy clusters (WOC). Conversely after evening hour HDC & MDS of overlap pattern faced hotter conditions due to long wave trapped radiation. However, the recorded reduction in afternoon and evening Ta of MDS were lower (2.2 °C & 1.7 °C) than in other study (Guangzhou, China) where the similar tree (canopy density, 2.5) had a (1.8 °C & 2.15 °C) reduction in evening and afternoon Ta respectively (Xinyi et al. 2024).

Furthermore, this is also in line with the finding of same study, where the dense trees clusters (fully shaded space) reduced the ambient temperature most efficiently. Therefore, it is recommended to implement current experiment of canopy and clusters based customized proposals for outdoor planting. However escalated values of Ta were observed both HDC & MDC when they exposed to afternoon solar radiation across all planting pattern. The notable heat stress thresholds for all thermal indicators Ta, MRT & UTCI were fixed as 0.50 °C, 5.0 °C, 3.0 °C respectively, (ISO 1985), (Morakinyo 2019). Additionally, different thermal variables (PET) were chosen for this investigation. This study also aligned with the findings of the completed in similar climatic context in, where the iteration with "abundance of trees with high crown density" shows reduction of 2.9 °C in Ta from no tree case in afternoon (Sachini J et al., 2024). The findings of the current study are confirmed by those of Cairo's built-up areas, where a 50% outside tree plantation improved street thermal comfort more effectively (Aboelata & Sodoudi., 2019).

Nevertheless, it is significant that planting area by overlap canopies clusters OC has resulted in a bigger reduction of 30% of UTCI from the base scenario. This is because when more trees are added, the magnitude of shading increases in terms of higher value of delta MRT & UTCI, (Pir et al. 2021), (Raje and Ojha 2022).

It is apparent from the simulated results that overlapped tree clusters spaced continuously provide a greater shaded region and thus optimize the thermal stress the outdoor environment (Saeid et al. 2020). Upon quantifying the iterations, the cooling effect of the without overlap clusters WOC design is regarded smaller due to the installation of widely spread and fewer trees. This indicates that the canopy density of the tree species has a greater influence on stress reduction than does cluster formation and tree spacing or canopy overlapping.

Variation in thermal stress mitigation by tree canopy density

It is important to examine the impacts of the tree canopy density and clusters on the thermal reduction potential so that it can be customized for certain outdoor space design with exclusive morphological attributes. It has been noticed that tree canopy-size/cluster-density is directly related to reduction of bio-meteorological thermal variables (MRT & PET etc.), (Raman 2021). The current study proposed that if a tree's morphological characteristics are identical, the canopy's density plays an important effect in wind movement at pedestrian level. In terms of the impacts of tree morphology, MDC & HDC had dissimilar cooling duration. Pattern with overlapping canopies OC yielded higher magnitude of benefits than those with WOC pattern, as the delta values of UTCI were relatively higher. When quantified by UTCI and applying HDC, the ground area cooled for 6 h (10:00 to 16:00) with almost average of reduced temperature of delta 10 °C. This needs to be said this approach (highly denser tree canopies) has been chosen in previous research as an influential factor in improving microclimate (Zhang et al. 2017), (Yang et al. 2018).

According to research on tree foliage density, the perceived air temperature decreases by 0.03 °C to 0.3 °C for every 1–10% increase in tree canopy density. Thus, on a summer afternoon, the perceived temperature would decrease by 2.5 °C in an area with a roughly 80%. dense tree canopy (Ali and Patnaik 2019). According to this study, the simulated stress reduction was comparable and greater for a highly dense canopy (HDC), which resulted in an afternoon reduction in Ta of 2.8 °C on average.

Implications of integrating evidence-based planting pattern for the efficient outdoor space design

The outdoor space design of our cities is significant because they have frequently established their own microclimates (Johansson and Emmanuel 2006). As therefore, the current study suggests a quantitative research strategy to evaluate the stress reduction potential of tree planting strategies. There are multiple ways in which this can be viewed in relation to microclimatic studies. Firstly, outdoor space design would require suggesting green retrofits such as the customized tree clustering techniques to develop efficient shading and in conjunction with site other physical attributes (Perini 2018). Secondly, solely planting sparse canopy density trees without overlapping clusters had fragile correlation in reducing outdoor thermal stress. However, predetermined concept of ad-hoc planting of trees with sparse canopy density in sparse clustering would not be beneficial for pedestrian comfort in day time extreme conditions. Thirdly, evidence-based implementation of tree spices would have a more effective impact on outdoor thermal comfort in accordance with the variability of overlapping trees clustering.

Future scope and constraints

The limitations of the study indicate potential areas for further investigation. At first, the research that was done for one season, covering open ground areas from morning to night, a comparison of monsoon season and associated discomfort would provide a deeper comprehension of planting design. Furthermore, this results strongly suggested on the evidence-based tree selection and planting design however, the ground surface treatment like hard and soft pavement also regulates outdoor microclimate (Ali and Patnaik 2018). Finally, to determine the most effective outdoor space design, it would be useful to conduct in-depth study on various outdoor shading devices such as pergolas, umbrellas, etc. with tree clusters.

Conclusion

The intention of this study was to investigate ways to modulate outdoor thermal stress using specific planting patterns and tree-canopy architecture. The conclusions are based on an actual site survey, coupled with measurements in the field and an Envi-met numerical simulation. The most significant contributions would be proposing evidence-based planting proposal and further quantifying the stress reduction potential of iterations based on densities and clusters. In fact, this study looked into four scenarios with high and moderate dense canopy, offering the possibility of developing clusters with canopy overlapping. Following that, the outdoor stress and its influence on pedestrians were computed across three thermal variables such as the air temperature, mean radiant temperature, and Universal Thermal Climate Index over a 24-hour period (morning to night).

Since there is very limited way to change the physical infrastructure of existing outdoor spaces due to city development requirements, modifying ground surfaces and trees is the most practical course of action. The clustering of trees as modulator of the microclimate in urban spaces should be established on evidence-based screening of selection process rather than being organised homogeneously across the spaces. To reduce thermal stress from a biometeorological perspective, this study revealed that moderately dense canopies trees should be clustered with overlapping pattern or highly dense canopies with without overlapping pattern.

It has been noticed that tree canopy-size/cluster-density is directly related to reduction of outdoor thermal stress, by permitting or preventing solar radiation along with controlling the wind movement. The analysis also showed that pattern generated from overlap canopy clusters were cooler and reduces the ambient temperature most efficiently than without overlap canopy clusters. Therefore, it is recommended to implement current experiment of canopy and clusters based customized proposals for outdoor planting. This study also discovers that when compared to half coverage and without coverage cases, a full coverage with a high canopy density considerably lowers MRT and UTCI. Nevertheless, it is significant that planting area by overlap canopies clusters has resulted in a bigger reduction of UTCI due to increase in the magnitude of shading. Therefore, it is important to examine the impacts of the tree canopy density and clusters on the thermal reduction potential so that it can be customized for certain outdoor space design with exclusive morphological attributes.

Although the results of this study can be applied and generalized to the city of Bhopal, the recommended tree canopy density, coverage and leaf area density cannot be generalized, as different outdoors settings with varied dimensions and orientations, result in entirely different outcomes. Though the research-methodology incorporated to determine the canopy density and planting pattern can be generalized with the similar iterations and quantifications techniques in similar climate context. Further studies on alternative ground surface materials could be intriguing to accommodate various thermal efficient materials. In landscape architecture and practices, the planting design strategy has been mainly guided by aesthetic preferences, site compatibility, and management however, this experiment highlights the significance of choosing thermally suitable planting pattern in compliance with the recent standards, (IRC:021 2009), (FSI 2015). Additionally, the development recommendations may be formulated based on an objective assessment of the of the tree selection procedures for the development of climate suitable outdoor design. Incorporating the findings of this study into design guidelines and city administration could benefit urban municipalities' decision-makers, designers, and stakeholders as they build new, more climate-adaptable communities.

Funding The authors declare that they this research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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