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EXAMINING THE INFLUENCE OF URBAN FORM ON THE THERMAL COMFORT OF STREET CANYONS IN TEHRAN: A CASE STUDY OF NARMAK NEIGHBOURHOOD

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ABSTRACT

As urbanization advances, the emphasis on outdoor spaces grows, highlighting poor thermal balance as a detrimental factor in achieving comfort within densely populated urban structures. Consequently, an urgent imperative exists to evaluate and optimize urban morphology to ensure sufficient outdoor thermal comfort. This study assesses the thermal efficiency of residential areas in Narmak, Tehran, Iran, with the primary goal of enhancing thermal comfort, specifically the PET, and discerning optimal urban layouts. Employing computational simulation techniques, this investigation meticulously examines urban design variables that influence outdoor thermal comfort, encompassing street direction, enclosure, building forms' typology, and tree planting. The research findings unveil that the orientation of street canyons exerts the most significant influence at 39.12%, closely followed by the aspect ratio at 36.78%. Remarkably, within the considered climatic components such as air temperature, wind speed, and humidity, tree planting emerges as the most influential factor impacting outdoor thermal comfort in this case study. These analytical outcomes furnish valuable insights into the contextual design of elements that influence the thermal comfort of outdoor open spaces.

Keywords: Outdoor Thermal Comfort, Urban Morphology, Street Canyons, Urban Heat Island, Urban Configuration

1.0 INTRODUCTION

The urban heat island (UHI) phenomenon is characterized by heightened temperatures in metropolitan areas compared to their surrounding regions, as documented by Yin et al. (2021). This predicament arises from the intricate interplay of urbanization processes and associated climate changes, as Salmanian and Ujang (2021) highlighted, contributing to increased energy consumption within urban locales due to heightened cooling demands, especially during heat waves. This, in turn, places additional stress on the power grid, as pointed out by Othman et al. (2021). The elevated ambient temperatures experienced in urban environments not only present health challenges, as identified by Shari and Dahlan (2023) but also underscore the growing importance of integrating comfort and health in defining well-being within the built Environment. This realization has spurred a heightened interest in outdoor comfort research, as observed in the work of Liu et al. (2022). The acknowledgment of responsive open spaces as integral to an elevated quality of living is on the rise, with outdoor thermal comfort emerging as a critical factor influencing the quality of outdoor open areas and consequently impacting people's engagement in outdoor activities. This trend has led to a significant surge in attention towards considering outdoor thermal comfort in the sustainable design of cities, as evidenced by Othman et al. (2019). Cities with hot and humid climates featuring elevated temperatures, humidity, and low wind speeds may experience exacerbated UHI effects.

In contrast, periods of warm weather act as catalysts for outdoor and semi-outdoor activities, prompting individuals to gravitate towards open environments without air conditioning, as De and Mukherjee (2017) observed. The geometric attributes of city blocks and building materials emerge as pivotal factors influencing Urban Heat Island (UHI) effects, underscoring the significance of well-conceived outdoor spaces and environments prioritizing thermal comfort. Such considerations have a positive impact on public health, well-being, tourism, the effective utilization of open spaces, and levels of social interaction, as elucidated in studies by Nasir et al. (2018), Ge et al. (2017), and Zhang et al. (2023). Despite these benefits, research by Mokhtar and Reinhart (2023) indicates a decline in outdoor activities with rising summer temperatures (Ta), leading to urban outdoor areas often needing more microclimate considerations in their design and needing to be more utilized. This issue is further exacerbated by the need for more practical and applicable urban planning design guides, as Kyprianou et al. (2023) emphasized.

Delving into the intricacies of thermal dynamics in outdoor environments within the Mediterranean region, this investigation hones in on the scorching summer climate prevalent in Tehran's Narmak Neighbourhood, Iran. The primary focus of this study revolves around the development of precise guidelines for urban design, with a specific emphasis on enhancing outdoor thermal comfort through the application of advanced computational optimization processes. This intricate process involves the utilization of parametric design methodologies and simulation techniques to fine-tune the thermal efficiency of Street Canyons. The overarching aim is to thoroughly and systematically evaluate the existing thermal conditions within the selected case study. Concurrently, the study seeks to strategically optimize urban design parameters to align seamlessly with the microclimate intricacies prevalent in the designated zones.

2.0 LITERATURE REVIEW

2.1 Thermal Condition In Outdoor Open Spaces

The nuanced comprehension of outdoor temperature perception is a multifaceted concern subject to local climate characteristics' influence, as Ravichandran and Gopalakrishnan (2023) illustrated. In high-density urban environments, scholarly inquiries discern three pivotal determinants influencing this perception, as illustrated by Liu et al. (2022): meteorological conditions, encapsulating solar radiation, humidity, and wind speed; individual health considerations; and psychological parameters. Amidst these environmental determinants, air temperature is paramount as the key microclimate element significantly shaping the perception of heat, as noted by Lee et al. (2023). Furthermore, the attainment of thermal comfort hinges on air temperature and additional climatic factors, including radiant temperature and wind speed, as elucidated by Ouyang et al. (2023). Of particular note, air movement surpassing velocities of 1.5 m/s exerts a substantial influence on the heat perception experienced by individuals in outdoor spaces, according to findings by Zhang et al. (2023). The Urban Heat Island (UHI) phenomenon, influenced by solar radiation patterns and various design factors, presents an opportunity for mitigation through alterations in building layouts, especially in temperate climates. This proposition is supported by the works of Salmanian and Bayat (2023) and Kaoutar, Ouali et al. (2018).

Moreover, a suitable urban configuration layout can aid in alleviating the adverse impacts of urban climate conditions. Despite extensive efforts to construct urban building configurations focused on enhancing thermal and climate comfort through scientific methodologies, it remains essential to regulate design aspects to ensure optimal influencing factors and establish standards. Additionally, in numerous cities, urban planners and designers overlook considerations of thermal comfort and environmental attributes when developing new urban areas, especially in hot climates where there is a greater need for thermal comfort, shaded areas, and improved airflow (Abd Elraouf et al., 2022).

A plethora of research endeavors have delved into an array of strategies designed to optimize outdoor thermal comfort, casting a spotlight on ventilation dynamics (Tang et al., 2023), material properties (Oquendo-Di Cosola et al., 2023), vegetative elements (Dong & He, 2023), and the presence of water bodies (Deng et al., 2023). Regarding high-density urban environments, scholarly inquiries discern three pivotal determinants influencing this perception, as illustrated by Liu et al. (2022): meteorological conditions, encapsulating solar radiation, humidity, and wind speed; individual health considerations; and psychological parameters. Notably, street canyons' aspect ratio and orientation emerge as pivotal considerations in urban planning, constituting critical factors that demand meticulous attention to optimize outdoor thermal comfort, as underscored by Deng et al. (2023). The following subsections offer a comprehensive overview of these influential factors, elucidating their roles in conjunction with the impact of urban surface conditions on the overarching domain of outdoor thermal comfort.

2.2 Enclosure

The enclosure (measured using aspect ratio), expounding on the correlation between the height of buildings and the width of streets, emerges as a pivotal parameter in urban planning, specifically in thermal comfort considerations (Zhang et al., 2023). Elevated aspect ratios and deeper street canyons wield the effect of diminishing sun exposure and temperatures, resulting in outdoor environments that register an approximate cooling of 3.5e6 oC (Zhang et al., 2023; Deng et al., 2023). Classifying canyons into shallow and deep forms, with aspect ratios less than 0.5 and equal to 2, respectively, an optimal aspect ratio of 1 is identified to create streamlined canyons (Bedra et al., 2023). Rodrı'guez-Algeciras et al. undertook an investigation, presenting suggested thresholds for the design parameter height to width as 1 and 1.5, aiming to attain satisfactory outdoor thermal comfort in both summer and winter seasons (Algeciras et al., 2016). Compact canyon shapes, characterized by lower aspect ratios, contribute to an elevated level of outdoor comfort, primarily attributed to the shading effect of neighboring buildings (Yahia et al., 2017). This heightened comfort level is particularly noteworthy in the summer, where shaded areas become preferred for outdoor activities, while sunlit spaces gain favorability in the winter (Yahia et al., 2017). The association between higher aspect ratios and reduced wind speed, coupled with wider streets leading to increased wind speed, reveals that alterations in wind speed within deep street canyons can induce temperature fluctuations of up to 5°C (Hao et al., 2023). In urban environments marked by high population density and towering structures, there is an elevation in mean radiant temperature (Tmrt) and outdoor wind speed. This starkly contrasts low-rise buildings, which typically induce a heightened perception of discomfort in urban outdoor settings.

2.3 Street Canyon Orientation

Numerous research investigations have underscored the critical role of street canyons' orientation and aspect ratio in shaping outdoor thermal comfort (Li et al., 2023). Findings from these investigations indicate that canyons aligned in a north-south direction provide the utmost comfort for individuals in outdoor settings, whereas those oriented east-west offer less favorable conditions, as Zhang et al. (2022) posited. Notably, east-west-oriented streets are particularly susceptible to intense solar radiation, resulting in elevated mean radiant temperature (Tmrt) values (Miao et al., 2023). Additionally, a consensus in multiple studies identifies the northeast-southwest orientation as the optimal layout for street canyons in urban planning (Yilmaz et al., 2022), with the north-south orientation deemed most conducive to favorable thermal comfort for outdoor residents. Nevertheless, this urban arrangement has inherent drawbacks, notably an increase in energy consumption required for building cooling, attributed to heat dissipation from outer walls and diminished exposure to sunlight, as elucidated by El-Darwish and Gomaa (2017).

The impact of street orientation on airflow coefficients at the pedestrian level constitutes a significant aspect of urban environmental dynamics (Chatzidimitriou & Axarli, 2017). Streets parallel to the prevailing wind flow exhibit elevated wind speeds, further intensified by reducing the aspect ratio within street canyons (Emmanuel et al., 2016). Perturbations in building height and the introduction of asymmetric aspect ratios can induce turbulence, consequently influencing ventilation patterns around tall structures (Song et al., 2023).

2.4 Surface Conditions In Urban Areas

Within urban spaces, the elevated temperatures of anthropogenic structures result in the outward dissipation of sensible heat, thereby elevating the air temperature (Ta) (Geletič et al., 2023). The surface temperature in urban open spaces plays a pivotal role in influencing the thermal conditions of outdoor open spaces. Consequently, design principles often advocate implementing east-west-oriented streets to optimize sunlight exposure (Ma et al., 2023). Incorporating high-albedo surfaces holds promise in mitigating temperatures within urban open spaces (Yakubu et al., 2023). A study conducted in 2017 demonstrated that a synergistic approach involving cool roofs, walkways, and augmentation of vegetative cover holds the potential to ameliorate the comfort index and mitigate correlated health hazards substantially, yielding a potential reduction of up to 60% (Kumar et al., 2023). During summer, vegetation is crucial in urban settings as it absorbs surface energy via photosynthesis and transpiration. Its ability to shade effectively also blocks solar radiation.

Moreover, the canopy of vegetation can slow down airflow, causing obstruction and decreasing wind speed (Chen et al., 2023). In urban areas, using vegetation as a heat-mitigation approach is preferred over employing high albedo materials on the ground to enhance pedestrians' thermal comfort. Greenery alters outdoor thermal conditions through various mechanisms, including evapotranspiration, sun reflection, shading, and airflow modification. Specifically, vegetation cools the Environment through transpiration, where absorbed solar energy leads to water evaporation from plant surfaces, thus reducing temperatures. These effects are typically quantified using a measure of cooling power per unit volume of vegetation based on leaf area density. Additionally, vegetation increases the overall reflectivity of short-wave radiation in the city, resulting in less heat absorption than building materials. Furthermore, tree canopies help prevent the escalation of air and surface temperatures by intercepting solar radiation (Gatto et al., 2020).

The introduction of green plants has been correlated with mitigating the effects of the Urban Heat Island (UHI) (Ramakrishnan et al., 2020). Through the deliberate manipulation of pivotal meteorological variables, namely temperature, wind speed, and relative humidity, the systematic deployment of trees at intervals of 4 meters has been empirically shown to engender a reduction in the mean radiant temperature by as much as 23°C in comparison to an arboreal-lacking urban milieu (Srivanit & Jareemit, 2020).

3.0 METHODOLOGY

The primary objective of this study is to systematically investigate and analyze the optimal urban design considerations for residential development in Narmak, Tehran, Iran. The research scrutinizes various influential design factors such as street canyon orientation, aspect ratio, building morphology, and the spatial arrangement of tree planting in outdoor spaces. The methodology employed in this research is visually represented in Figure 1, depicting the systematic workflow. Within this workflow, the ENVI-met tool and the Physiologically Equivalent Temperature (PET) index are integral components as analytical instruments to evaluate the existing street configurations and the envisioned scenarios designed for the study.

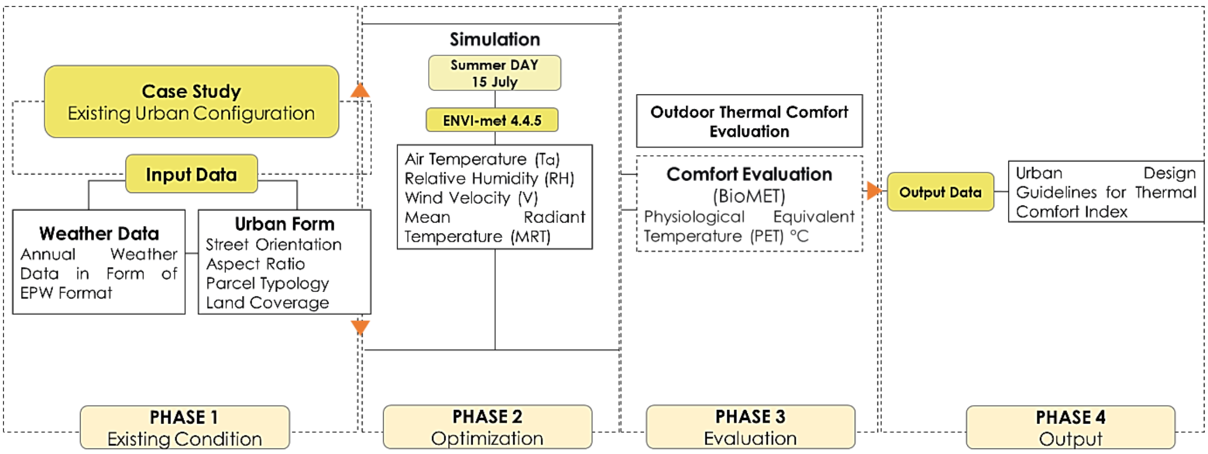

Fig. 1: Flowchart demonstrating the research procedure

3.1 Case Study

Narmak, situated in the eastern part of Tehran, is a crucial residential expansion area. The anticipated growth in housing units poses the potential for significant alterations in the microclimate conditions of Narmak's streets, leading to unfavorable outdoor thermal environments. Narmak encompasses three distinct road widths and two intersecting alignments. The residential zones within Narmak are characterized by either local 2-lane roads (7m in width) or secondary 4-lane roads (10m in width), with a limited number of primary 6-lane roads (15m or more). For this study, a 6-lane road, segregated and located away from residential areas, was not included in the evaluation. The study adopts a width of 8m for a two-lane road, where the primary thoroughfare features conventional black asphalt and a 1.5m wide concrete pavement (refer to Figure 2).

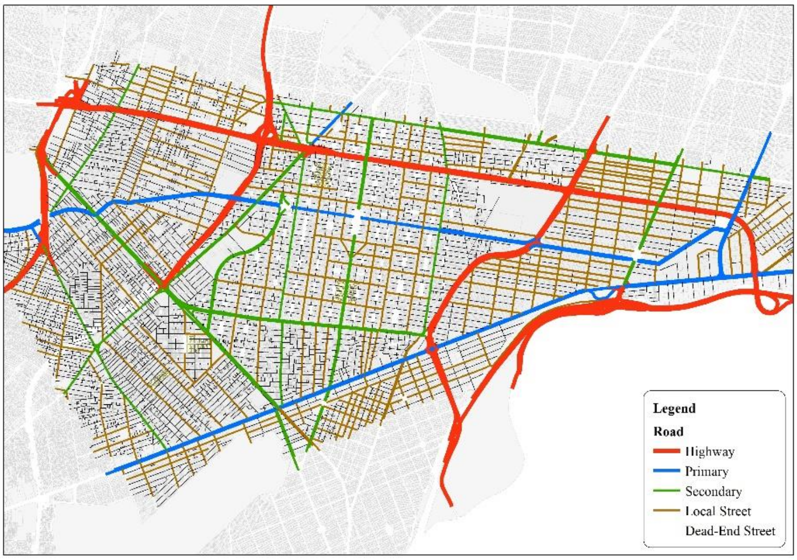

Fig. 2: Street Morphology, width, and orientation in the study area

Three orientations, namely North-South, East-West, and Northwest-Southeast, exhibit nine variations, encompassing the majority of the neighborhood blocks (refer to Fig. 3). The residential structures comprise attached houses ranging from 1 to 5 stories, featuring brick as the predominant facade material. An average height of 12 meters has been established to adhere to regional roofing standards. Typically, dwellings are positioned adjacent to the main street canyon, characterized by extensive tree coverage. This placement influences the microclimate of the surrounding streets by augmenting greenery and concurrently mitigating the urban heat island effect.

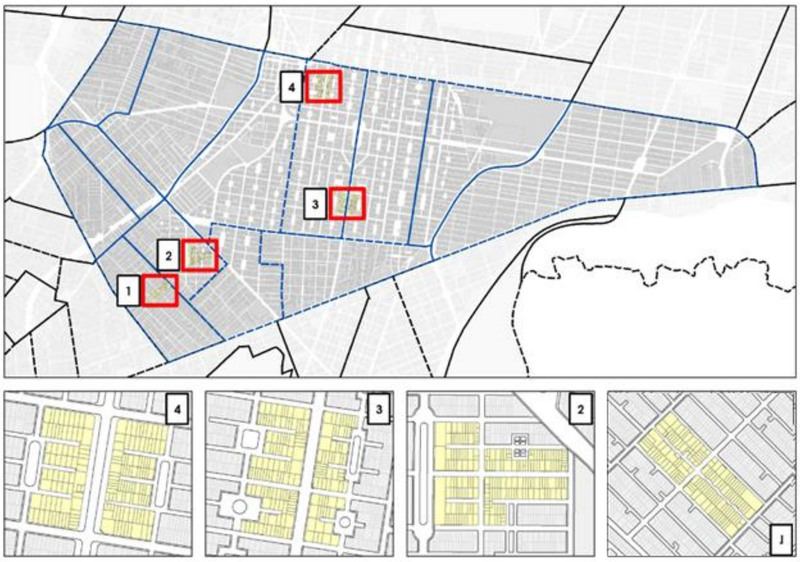

Fig. 3: Defining the study area location and urban morphology

3.2 Research Design

This research employs a comprehensive simulation approach to investigate the optimal layout for urban design parameters such as street orientation (north-south, east-west, northeast-southwest, southeast-northwest), building classification (linear and singular), enclosure (ratio of 0.5, 1, 1.5, 2), and tree planting patterns (based on the thermal Environment) at 5m and 10m intervals. The simulation incorporates a 2m-wide swath of greenery, representing the minimum width dictated by the modeling mesh. Diverse spatial intervals, specifically 5 and 10 meters, are being examined to assess the influence of green spaces on al fresco thermal comfort. This investigation explores two distinct planting configurations: one with denser foliage and the other exhibiting sparser vegetation. This study adopts an iterative and phased approach in the independent analysis of each design element to derive urban planning guidelines focused on enhancing thermal comfort. Each element undergoes isolated simulation, and the most effective option is iteratively advanced to subsequent phases. The collective evaluation of variables occurs only in the succeeding stage. The influence of tree planting on outdoor thermal comfort is assessed, and the least effective option (0.5 aspect ratio) is chosen as the input for the next phase. This selection is rooted in the premise that roads in optimal configurations (aspect ratio of 2) already offer satisfactory thermal comfort levels, obviating the need for further enhancements like introducing water bodies and additional green areas.

Consequently, the effort shifts towards achieving optimal thermal conditions by implementing the identified tree planting pattern on a road with an aspect ratio of 0.5. The building component of the study considers the prevalent facade material in Narmak, which is brick, streamlining computational processes. The characteristics of highway and sidewalk surfacing remain consistent with existing conditions. Table 1 and Figure 4 provide a detailed overview of various urban design scenarios, outlining the proposed dynamic tuning parameters.

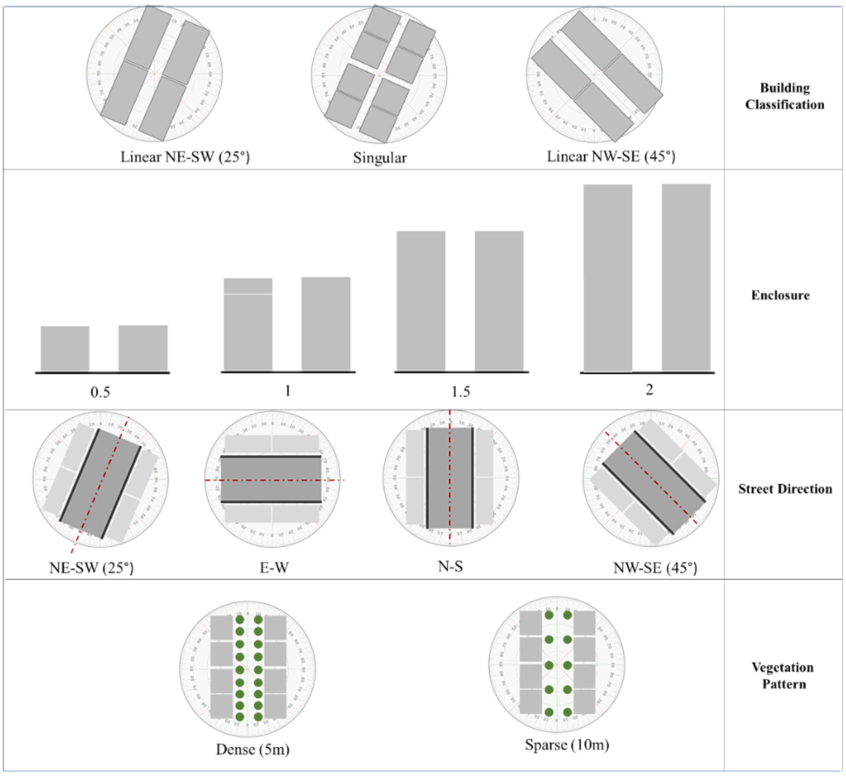

Fig. 4: Research Design Variables

Table 1: Proposed scenarios for the design process

Building Classification	Linear NE-SW	Singular		Linear NW-SE
Enclosure	0.5	1	1.5	2
Street Direction		NE-SW	E-W	NW-SE
Vegetation Pattern	Dense (5m)		Sparse (10m)	

3.3 Computer-Aided Simulation

Given the intricate nature of urban climate studies, numerical simulation emerges as a highly effective methodology for research at the point of sale, with a preference for computational approaches due to the extensive array of morphological variables (Gangwisch et al., 2023). Although various studies have utilized computer simulations (Zhang et al., 2022; Li et al., 2023; Huang et al., 2023), the current investigation utilizes computational simulations of microclimate conditions to scrutinize 14 distinct design scenarios employing the 3D modeling tool ENVI-met. ENVI-met, introduced by Bruse in 2004 (Wang et al., 2021), is a microclimate-centric tool that yields precise values for critical parameters, including air temperature, MRT, relative humidity, wind speed, and solar radiation. The reliability of ENVI-met in providing accurate data closely mirroring real-time meteorological conditions, particularly in summer calculations, has been firmly established. BioMET (V2.0) is also employed for PET calculations in this investigation. The urban microclimate dynamics are simulated by ENVI-met, employing atmospheric physics and heat transfer principles. The 3D wind flow is computed using the incompressible, non-hydrostatic Navier-Stokes equations with the Boussinesq approximation. Simulations in ENVI-met typically span 24-48 hours, with the optimal start time being at night or sunrise to align with atmospheric processes. Input parameters defining the 3D geometry of the target area, including buildings, vegetation, soils, and receptors, are necessary for ENVI-met simulations. Key input data comprise weather conditions, urban geometry, material properties, and vegetation characteristics. However, it is worth noting that ENVI-met has limitations in simulating the entire city's microclimate due to the restricted number of grid cells (Bochenek & Klemm, 2021).

In the course of this inquiry, an analytical mesh characterized by a cell size of 2*2 m² is employed, and its validation ensures the production of reliable data with an elevated level of precision, concurrently reducing computation time when juxtaposed with high-resolution models featuring smaller cells, as demonstrated by Salata et al. (2015). Within the confines of the 3D model, the specified spatial domain comprises a 100m street canyon, equivalent to 50 cells along the length of the grid. The outcomes are extracted at a height of 1.4m above the ground, representative of the standing height of an individual, thereby facilitating the evaluation of user comfort levels in outdoor environments.

3.4 Evaluation And Verification Of The Thermal Comfort

PET is prominent in hot and humid climates, as evidenced by a comprehensive literature review on outdoor thermal comfort in 2020 (Binarti et al., 2020). The definition of PET revolves around "the air temperature at which the core and skin temperatures are equal under the conditions studied, and the thermal equilibrium of the human body is maintained." The index in question is predicated upon a streamlined human energy balance model, specifically employing the Munich Individual Energy Balance Model, which was initially introduced under the German guideline VC13787 (VDI, 2008; Su et al., 2023).

Numerous investigations (Christine & Matzarakis, 2016; Briegel et al., 2023) have asserted the significance of Physiologically Equivalent Temperature (PET) as a pivotal metric for assessing outdoor comfort. PET involves the computation of Mean Radiant Temperature (Tmrt), utilizing a composite of global temperature, air temperature, and wind speed to gauge outdoor thermal comfort (Yahia et al., 2017). The BioMET PET calculations integrate user-specific factors, such as clothing condition and metabolic rate index, with meteorological parameters. In this context, the anthropometric profile adopts a model representing a 30-year-old male weighing 85 kg, height of 1.70 m, clothing insulation, and metabolic rate of 0.8 W/m² and 85.11 W/m², respectively. The derived Physiologically Equivalent Temperature values elucidate the temporal extent within the comfort range from 6:00 to 18:00 on a standard summer day. Table 2 provides default parameters for diverse thermal sensations and the associated thermal loads, each corresponding to specific PET regions.

Table 2: Physiological Equivalent Temperature thermal sensation/thermal stress estimate of outdoor open space

Thermal sensation/stress	PET (°C)
Extreme cold stress	-
Very strong cold stress	-
strong cold stress	<4
Moderate cold stress	4-8
Slight cold stress	8-18
Comfortable	18-23
Moderate heat stress	23-25
Strong heat stress	35-41
Very strong heat stress	>41

(Source: Matzarakis & Helmut,1996)

The assessment of simulation accuracy hinges on using Root Mean Square Error (RMSE) as a pivotal metric. The Honeybee plug-in is employed in this study, a well-established tool acknowledged in prior research for evaluating comfort conditions in urban outdoor environments (Geletič et al., 2023). Hourly temperature data generated by two distinct simulation engines, namely Compare Energyplus and ENVI-met, undergo a comparative analysis based on identical city configurations to gauge the precision of the models. The results reveal a strong correlation coefficient of 0.87 between temperature parameters assessed by the Honeybee and ENVI-met tools, affirming the model's high precision and the notably elevated R^2 value. Additionally, the Mean Square Error mathematical approach quantifies the deviation between simulated values obtained from the Honeybee plug-in and the ENVI-met software. The resulting minimal Root Mean Square Error (RMSE) values, specifically equating to 1.37, underscore the selected framework's reliability and validate the accuracy of microclimate condition simulations within the specific case studies.

3.5 Weather Data

The period characterized as the hot season in Tehran spans approximately 3.6 months, extending from May 29 until September 18. During this phase, the typical daily maximum temperature exceeds 87°F. Among these months, July is the hottest, with an average high temperature of 97°F and a corresponding low of 77°F. Conversely, the cool season spans around 3.5 months, commencing on November 24 and concluding on March 8, during which

the average daily high temperature remains below 57°F. The chilliest month in Tehran is January, registering an average low of 35°F and a high of 47°F (Figure 4).
To explore the influence of diverse urban layouts on the perception of heat among outdoor inhabitants, the date of July 15, notable for its high summertime temperatures, was selected. Within the scope of this study, a 24-hour simulation duration was adopted to capture the daily fluctuations in temperature.

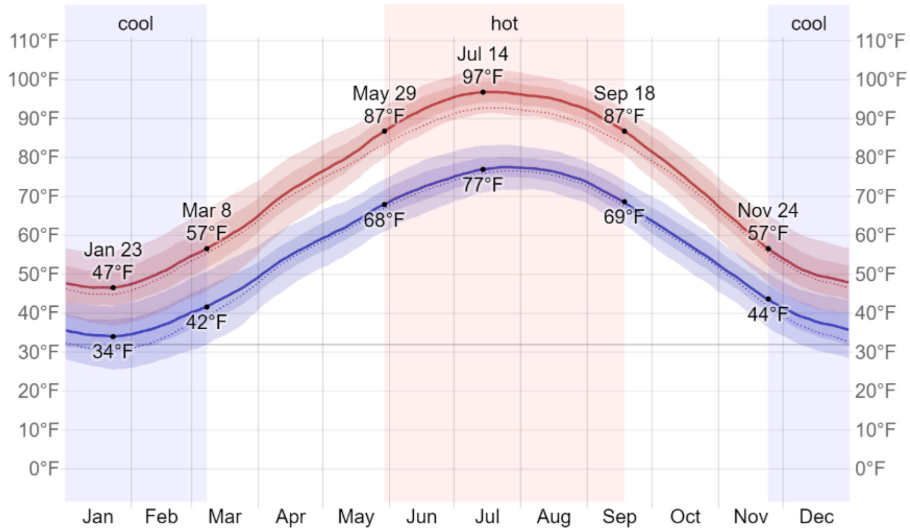

Fig. 5: The mean high temperature (depicted by the red line) and mean low temperature (illustrated by the blue line) for each day are presented, accompanied by the ranges spanning from the 25th to 75th percentiles and from the 10th to 90th percentiles. The faint dashed lines represent the average perceived temperatures that correspond to the data above points
(Source: https://weatherspark.com/y/105125/Average-Weather-in-Tehran-Iran-Year-Round#Figures-Temperature)

Tehran displays a moderate fluctuation in its average hourly wind speed over a year. The period marked by elevated wind activity spans approximately 7.1 months, extending from February 11 through September 14, during which the average wind velocities exceed 5.4 miles per hour. Notably, the zenith of windiness transpires in June, manifesting an average hourly wind speed of 6.5 miles per hour. Conversely, a phase of relative tranquillity prevails for around 4.9 months, encompassing the interval between September 14 and February 11. Within this interval, December emerges as the most placid month in Tehran, featuring an average hourly wind speed of 4.3 miles per hour (Figure 5).

Humidity assessment is predicated upon the comfort criterion of the dew point, a parameter instrumental in discerning the potential for perspiration to undergo evaporation from the skin, thus effectuating bodily cooling. Diminished dew points indicate diminished moisture content, yielding a sensation of dryness, whereas elevated dew points evoke an augmented sense of humidity. Unlike temperature, characterized by conspicuous diurnal fluctuations, the dew point exhibits a propensity for more gradual transformations. Consequently, although temperature fluctuations manifest prominently from day to night, a day typified by muggy conditions tends to be succeeded by night similarly imbued with mugginess. The perceived magnitude of humidity within Tehran, quantified through the proportion of time wherein the comfort threshold for humidity is gauged as muggy, oppressive, or distressing, evinces nominal seasonal variance, maintaining an almost unchanging 0% threshold throughout the year (Figure 6).

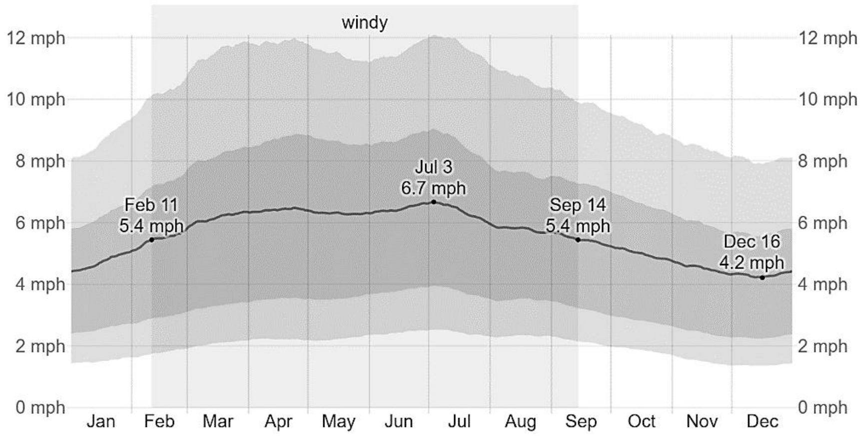

Fig. 6: The mean of hourly wind speeds (represented by the dark grey line), along with the interquartile range (25th to 75th percentiles) and the decile range (10th to 90th percentiles), is depicted

(Source: https://weatherspark.com/y/105125/Average-Weather-in-Tehran-Iran-Year-Round#Figures-WindSpeed)

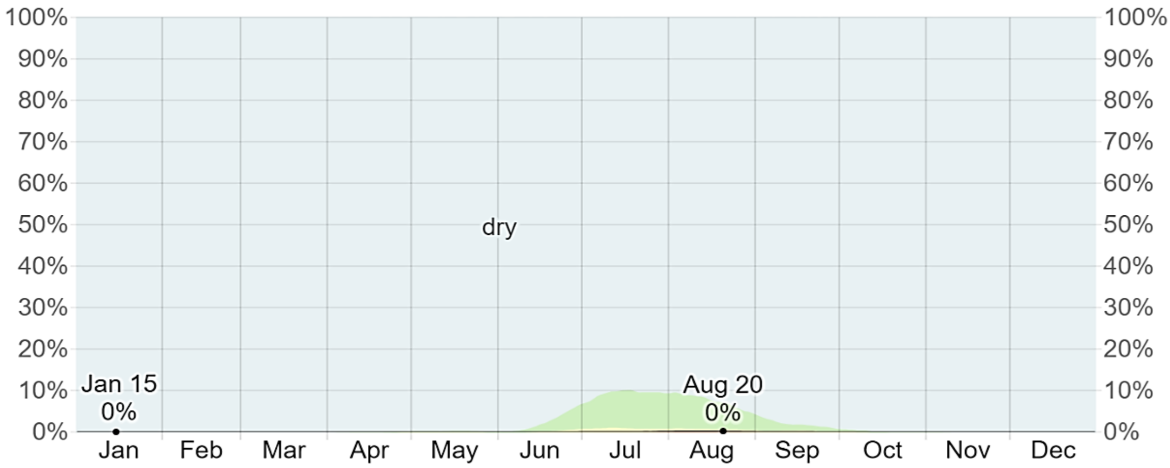

Fig. 7: The proportion of time allocated to different humidity comfort categories, classified based on dew point levels

(Source https://weatherspark.com/y/105125/Average-Weather-in-Tehran-Iran-Year-Round#Figures-Humidity)

4.0 RESULTS

The case study analysis yields insights into the thermal conditions of residential streets in Narmak. Notably, roads aligned along the east-west axis exhibit superior thermal comfort levels compared to their north-south counterparts, evidenced by daytime Physiologically Equivalent Temperature (PET) values within the comfort range of 14.35% throughout the day (6:00-18:00). The design parameters associated with road width, however, do not precipitate significant alterations in thermal conditions. The limited discernible influence can be ascribed to the slight difference in their measurements (2m) and the comparatively modest height of neighboring structures. Figure 8 visually illustrates the detailed hourly frequencies of PET across various case studies.

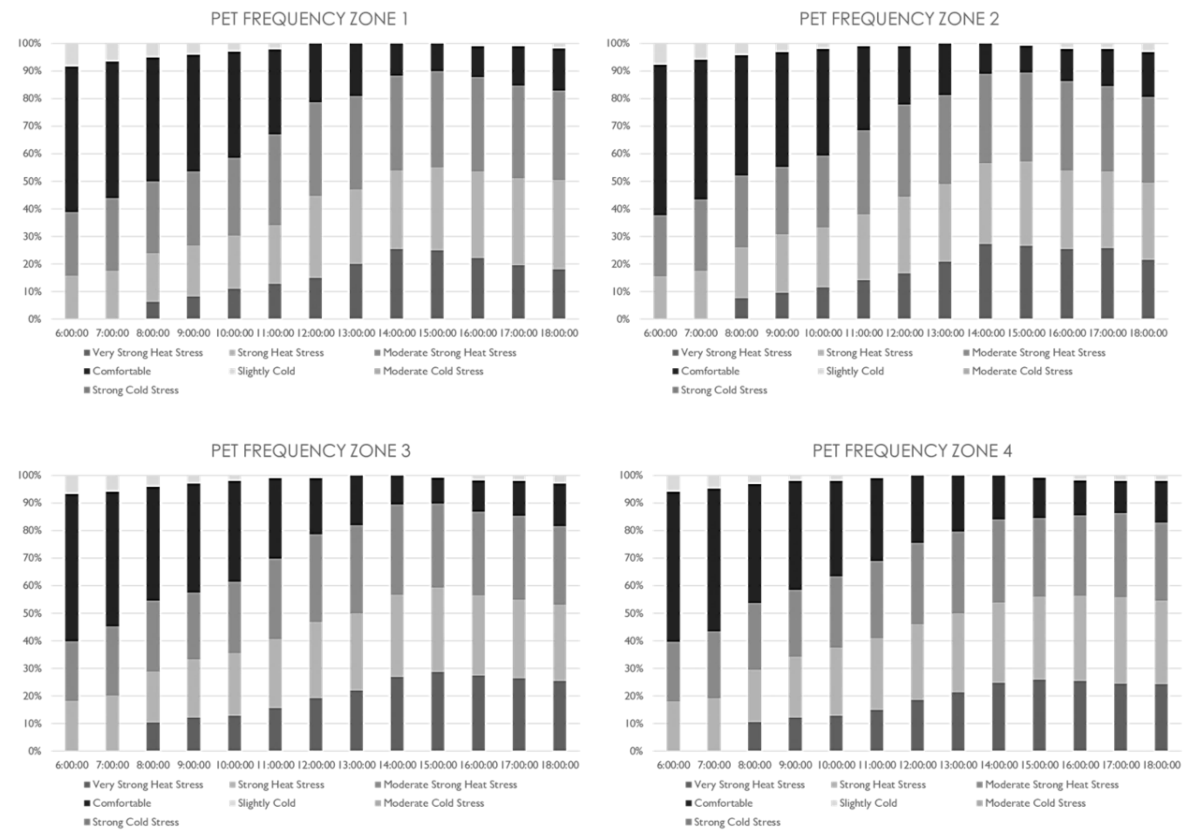

Fig. 8: Frequency of Physiological Equivalent Temperature (PET) from 6:00:00 a.m. to 6:00:00 p.m. in Zones 1-4 within Narmak Neighbourhood.

Streets aligned in the north-south direction significantly influence both humidity and wind speed, showing an average rise of 5.08% and 14.03%, respectively, as illustrated in Figure 9. A comparison between these north-south-oriented streets and their east-west counterparts reveals a notable difference of 3.98 m/s in airflow during the peak hour (3:00 pm) and a deviation of 9 degrees from the central axis. In the residential region of Narmak, a road with a half-width exhibits elevated wind speeds when contrasted with a narrower street. Precisely, a 10-meter-wide road leads to an average daytime wind speed elevation of 3.21% compared to an 8-meter-wide road. The air temperature values remain constant across the four chosen case studies, whereas the mean radiant temperature parameter shows less than five °C variances.

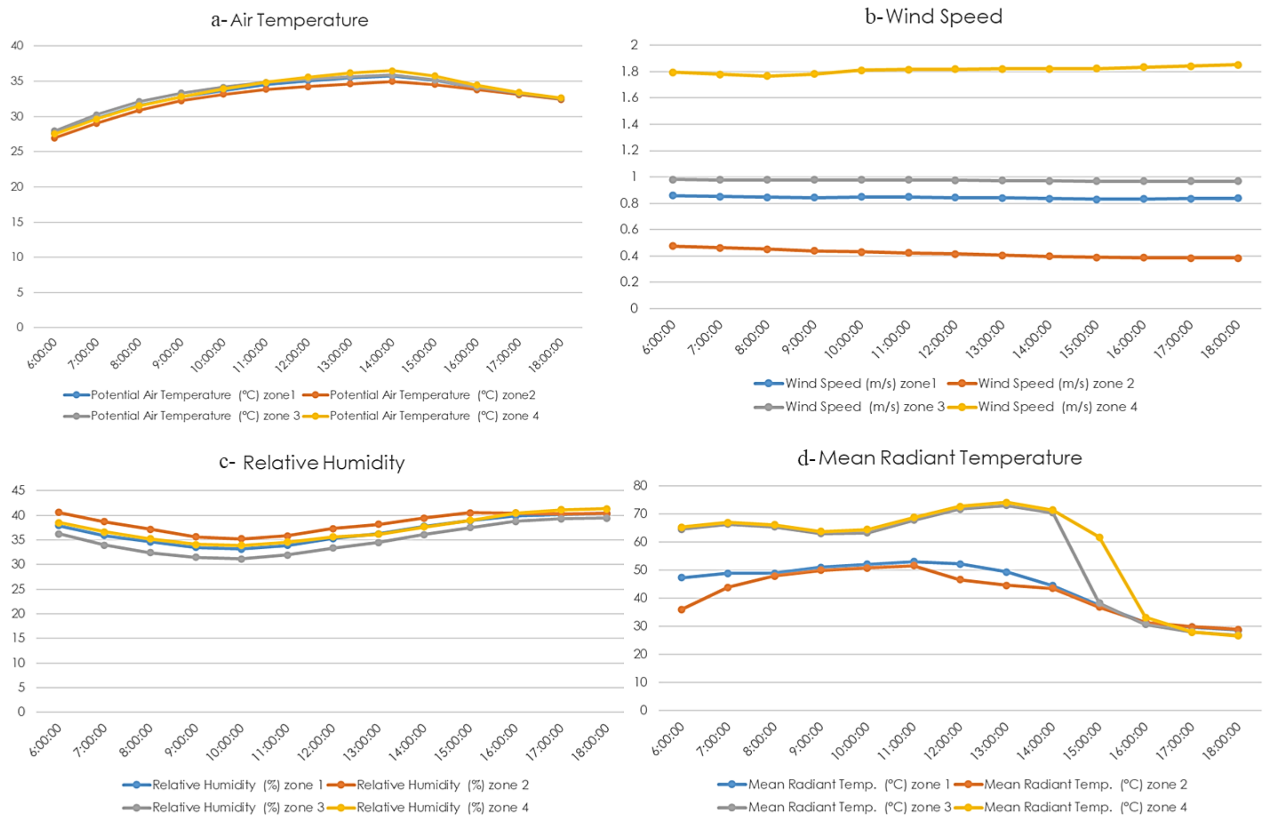

Fig. 9: a- Comparative assessment of Potential Air Temperature (°C) status in zones 1-4. b- Comparative Wind Speed (m/s) status analysis in zones 1-4. c- Comparative evaluation of Relative Humidity (%) status in zones 1-4. d- Comparative examination of Mean Radiant Temperature (°C) status in zones 1-4.

4.1 Street Direction

This study's primary focus of investigation centers around street orientation, recognized as a paramount design element in urban planning geared towards enhancing outdoor thermal comfort. Illustrated in Figure 10-a, the findings reveal that the NE-SW axis-oriented road surpasses alternative roads in the other three directions by an average of 34.73%, establishing this urban configuration as providing the highest level of thermal comfort. This layout creates a thermally comfortable environment for outdoor users, particularly during the hottest months, from 10 am to 4 pm. At different periods throughout the day, the felt warmth remains "mildly cool," deemed satisfactory and favorable. This perceptual result is largely shaped by meteorological elements, with a key emphasis on the impact of wind speed in the context of elevated air temperatures (Ta) characteristic of a typical summer day. When combined with shaded areas, wind speed becomes a vital factor influencing thermal comfort. Therefore, it can be affirmed that the orientation of streets, a fundamental aspect of urban planning, notably affects Physiologically Equivalent Temperature (PET) values, particularly wind speed and direction.

The North-South orientation of the street canyon (as illustrated in Figure 10-b) emerges as the second most pivotal priority in the realm of outdoor thermal comfort-based urban design, providing thermal comfort for outdoor spaces approximately 32.17% of the time throughout the day. In contrast, the northwest-southeast direction is deemed the least favorable road option for outdoor thermal comfort in an urban setting (refer to Figure 10-d). With a rise in the duration of sunlight, an increase in Mean Radiant Temperature (Tmrt), and a decline in wind speeds, individuals in open areas encounter discomfort in thermal conditions. These two elements, namely solar radiation and wind speed, are the primary climatic factors that significantly impact the comfort level of outdoor environments. Roads oriented in the northwest-southeast direction encounter "moderate heat stress" approximately 30.23% of the time. The second least favorable street canyon orientation is E-W, which enhances early morning thermal comfort and increases daytime heat stress. Strategies to improve comfort in these orientations may involve increasing shade effects, optimizing skyscraper design (higher aspect ratio), and implementing strategic tree planting. In all potential orientations of street canyons, a uniform perception of 'slightly cooler' temperatures is noted during the early morning (before 8 am) and late afternoon (after 5 pm).

Moreover, the perception of heat is significantly influenced by climatic parameters, particularly those associated with street canyon orientation. In this context, east-west-oriented roads exhibit the highest average mean radiant temperature at 33 °C, resulting in a moderate heat load persisting throughout the day. This parameter experiences a notable reduction to 8.24% for northeast-southwest-oriented roads, signifying an optimal urban design for thermal comfort. The average wind speed for the most favorable option (Northeast-Southwest Road) is 59.09% higher than that of the Northwest-Southeast Road (Figure 10-d). Meanwhile, meteorological factors like humidity and temperature remain relatively stable compared to alternative orientation choices. As a result, the most favorable configuration of road layouts leads to achieving optimal wind speeds.

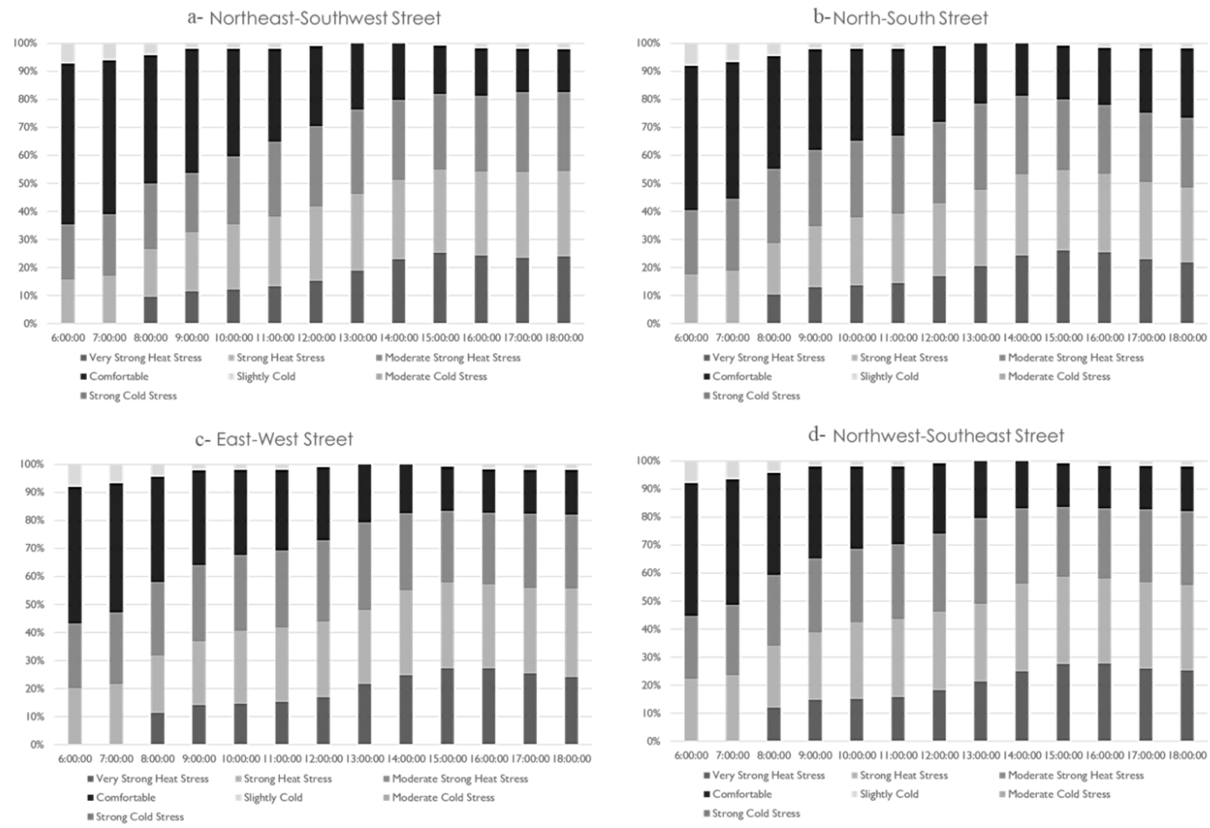

Fig. 10: a- The impact of streets situated in the northeast-southwest orientation on the frequency of PET. b- The influence of streets oriented in the north-south direction on the frequency of PET. c- The consequence of streets oriented in the east-west direction on the frequency of PET. d- The impact of streets oriented in the northwest-southeast direction on the frequency of PET.

The comparison between the orientations of street canyons highlights significant differences in their impact on outdoor thermal comfort. The NE-SW axis-oriented road stands out as the most favorable option, providing the highest level of thermal comfort, with an average improvement of 34.73% compared to alternative orientations. This layout ensures a thermally comfortable environment, particularly during the hottest months, maintaining a perception of "mildly cool" temperatures throughout the day. In contrast, the northwest-southeast direction is identified as the least favorable option, experiencing moderate heat stress for a considerable portion of the day. Similarly, while offering early morning comfort, E-W orientation increases daytime heat stress. Strategies to address these challenges involve increasing shade effects and optimizing building design. Moreover, the perception of heat is significantly influenced by climatic parameters, particularly mean radiant temperature, which is notably lower in NE-SW-oriented roads than in E-W orientations. Additionally, wind speed plays a crucial role, with the most favorable orientation (NE-SW) experiencing significantly higher average wind speeds, contributing to enhanced thermal comfort.

4.2 Building Classification

In the context of this investigation, it has been determined that the influence of building typology on outdoor thermal comfort is comparatively minor when contrasted with other factors that make up urban morphology. The research outcomes reveal that the linear arrangement of buildings along the northwest-southeast axis (depicted in Figure 11-c) is identified as the more comfortable option among the two alternatives—singular and extended linear northeast-southwest typologies—signifying a thermal environment of superior quality. However, despite the observed comfort, this specific design element does not instigate noteworthy alterations in Physiologically Equivalent Temperature (PET) values, relegating its significance to a less critical role in outdoor thermal comfort-based urban planning. The inter-building spacing on northeast-southwest-oriented streets, typically associated with the linear typology, notably fails to enhance thermal conditions. Hence, avoiding incorporating this arrangement in urban planning solutions is recommended. Even though the linear typology intersects the street direction, the orientation and aspect ratio of the design elements remain consistent among these three building typology alternatives, leading to minimal disparities in comfort conditions based on the current favorable thermal performance findings.

The investigation reveals that the maximum wind speeds are observed in a linear building configuration extending in the northeast-southwest direction. Notably, there is a reduction in wind speed by 4.57% to 2.29% in the northwest-southeast alignment for both extended and singular building typologies (refer to Figure 11-c). Importantly, these three building typologies display no significant changes in other climatic parameters, with variations in relative humidity and mean radiant temperature ranging from 1% to up to 2 °C.

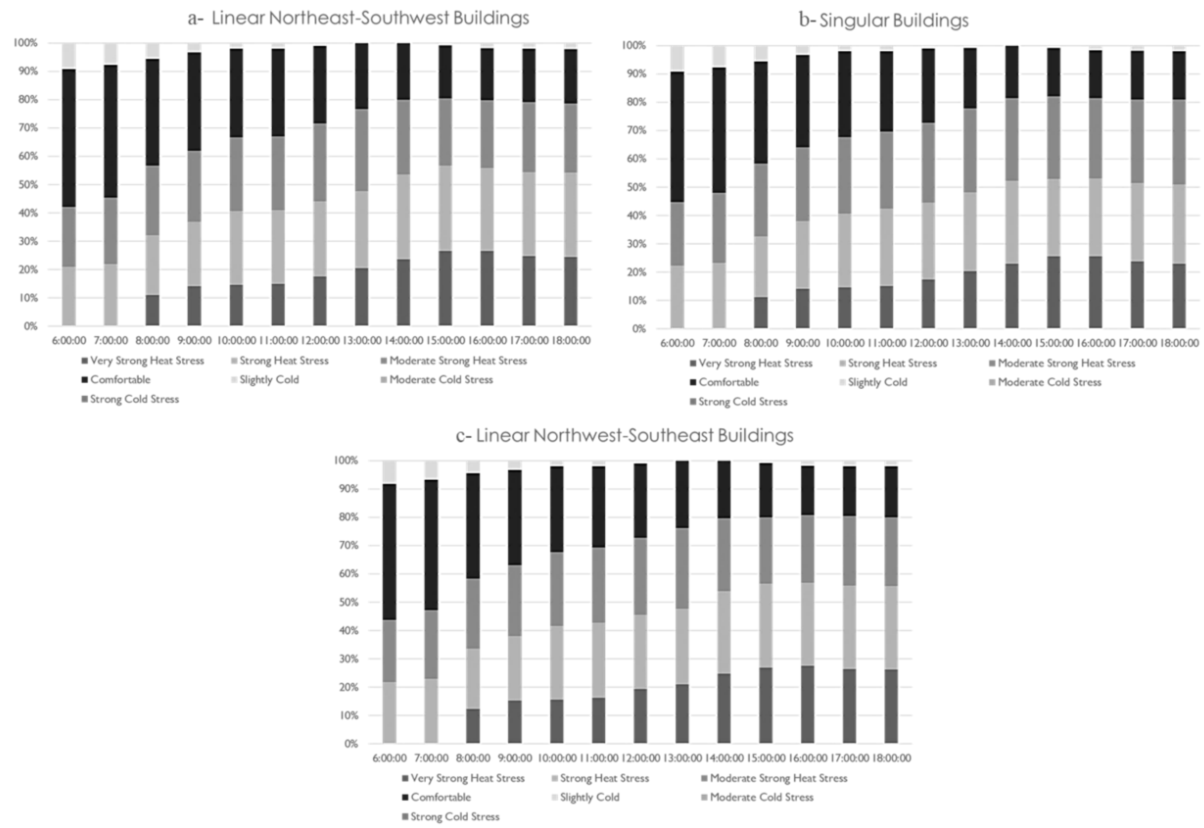

Fig. 11: a- The impact of buildings arranged in a linear northeast-southwest direction on the frequency of PET. b- The influence of individual buildings on the frequency of PET. c- The consequence of buildings arranged in a linear northwest-southeast direction on the frequency of PET.

The primary similarity among these classifications is their minimal impact on Physiologically Equivalent Temperature (PET) values, indicating that building typology has a comparatively minor influence on thermal comfort compared to other urban morphology factors. Despite providing a more comfortable thermal environment, the linear northwest-southeast axis arrangement does not significantly alter PET values, suggesting its limited significance in outdoor thermal comfort-based urban planning. However, a notable difference lies in the wind speed observations, where maximum wind speeds are observed in the linear configuration extending in the northeast-southwest direction. This reduces wind speed in the northwest-southeast alignment for both extended and singular building typologies. Additionally, these three typologies exhibit consistent orientations and aspect ratios, minimizing disparities in comfort conditions based on thermal performance findings. Furthermore, there are no significant changes in other climatic parameters, such as relative humidity and mean radiant temperature, among the different building typologies

4.3 Enclosure

The enclosure (aspect ratio), identified as the second most critical urban design element contributing to the delineation of a thermally comfortable urban environment, underwent meticulous adjustments through northeast-south orientation and the elongation of buildings along a straight northwest-southeast axis—an arrangement explored within the framework of street composition. Increasing the aspect ratio by 0.5 yielded an average reduction of

2.90°C in the maximum mean radiant temperature during the early morning and evening, resulting in decreased Physiological Equivalent Temperature (PET) values. The transition from a design parameter value of 0.5 to 1 extended the duration of comfort by 30.59%. Nevertheless, it is cautioned not to increase the aspect ratio beyond one in this area with elevated wind speeds, as it shifts the comfort range and results in moderately cooler road conditions for most of the day, particularly at 6:06 pm. An increase of 0.5 in the aspect ratio resulted in an average reduction in thermal comfort of 2.22%. As a result, maintaining the aspect ratio at one is recommended for buildings oriented along the northeast-to-southwest axis.

In contrast, case studies with a ratio of 0.5 accentuated the average heat load from 10 am to 3 pm. Achieving satisfactory comfort levels necessitates elevating the aspect ratio value, thereby increasing the proportion of horizontal surface shading. As the aspect ratio undergoes augmentation, there is a corresponding decline in the average radiant temperature. Specifically, the Mean Radiant Temperature Index (MRI) parameter registers a decrease of 3.31°C (13.23%) for every 0.5 increase in the ratio value. Notably, no significant alterations were observed in wind speed or humidity levels during these adjustments.

4.4 Vegetation Pattern

Implementing vegetation and tree planting represents an additional effective parameter that merits consideration for enhancing thermal conditions within urban streets, particularly for roadways characterized by suboptimal orientation and low-rise buildings, as exemplified by an optimized city layout with low buildings having an H/W ratio of 0.5.

By employing densely planted trees at a spacing of 5 meters, the Physiological Equivalent Temperature (PET) value can be reduced by as much as 12.07% (as illustrated in Figure 12-b). However, when adopting a sparser planting pattern, this reduction may decrease to 7.83% (as depicted in Figure 12-c). These findings offer valuable insights for mitigating PET levels in urban locales where creating comfortable thermal environments is challenging.

The introduction of greenery and planting of trees contribute to an increase in relative humidity of a maximum of 1.1%, thereby enhancing the thermal comfort of the streets. Furthermore, the consolidation and strategic removal of plantations reduce the average mean radiant temperature from 1.23 °C to 1.12 °C.

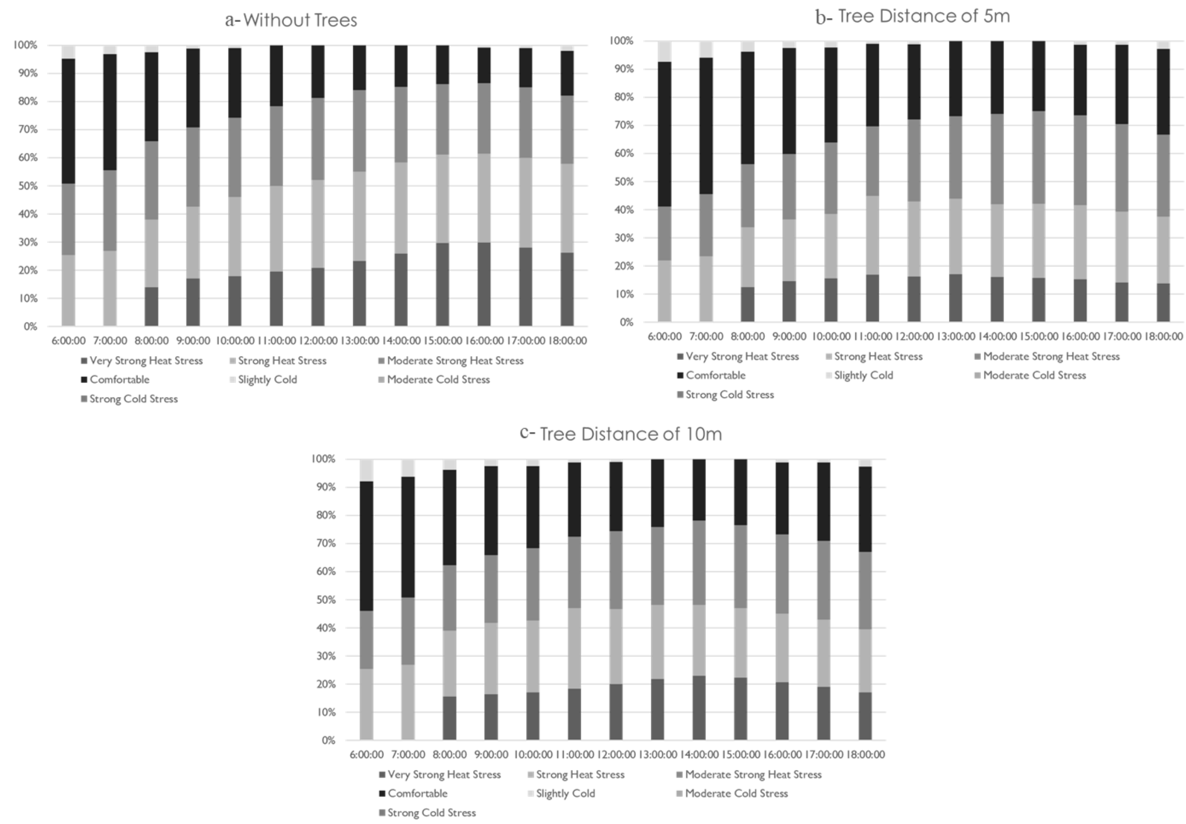

Fig. 12: a- The impact of the absence of trees on the frequency of PET. b- The influence of tree planting at a distance of 5 meters on the frequency of PET. c- The consequence of tree planting at a distance of 10 meters on the frequency of PET.

5.0 DISCUSSIONS

The predominant residential neighborhoods in Narmak must establish an urban environment that aligns with thermal comfort standards. Manifestations of heat stress are conspicuously evident on north-south roads, lingering for several hours each day yet imparting a perceptibly satisfactory sense of warmth. This perceptual outcome is primarily ascribed to the constrained utilization of the "aspect ratio" parameter, diminishing shadow effects and elevating the average radiant temperature in the street canyons. The distribution of time spent daily in a comfortable thermal environment across various case studies is depicted in Figure 13. Comparing the trends of potential air temperature between honeybees and ENVI-met data reveals a consistent pattern of temperature variation throughout the day. Both datasets show an increase in temperature from the early morning hours to midday, followed by a gradual decrease towards the evening. This pattern aligns with the expected diurnal variation in temperature in outdoor environments. However, there are slight discrepancies in the recorded temperatures between the two datasets at each time interval. Overall, Honeybee tends to report slightly higher temperatures compared to ENVI-met data across most of the recorded hours. Despite these differences, both datasets depict a similar trend of temperature fluctuation over the day, indicating a general agreement in capturing the overall temperature dynamics within the studied area.

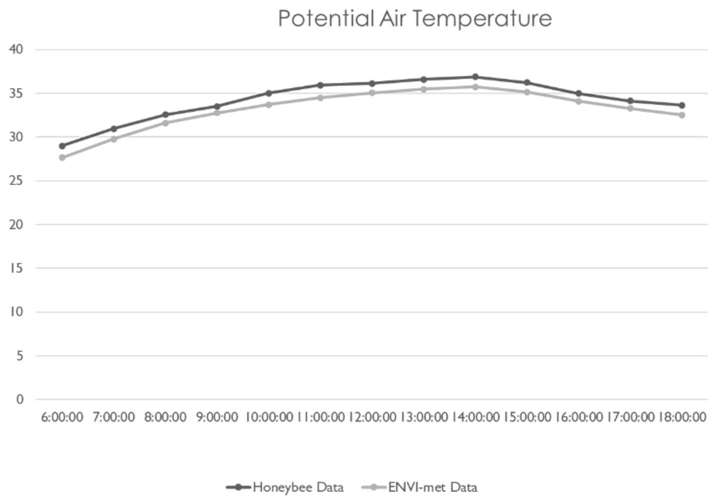

Fig. 13: Potential Air Temperature status from Honeybee and ENVI-met tool

The main objective of this investigation is to improve the thermal conditions of outdoor areas, thereby enabling their potential integration into future urban development and planning initiatives. Among the aspects studied in urban planning, street orientation was the most impactful at 39.12%, followed closely by aspect ratio at 36.78%, area ratio (connected to greenery), and building type. As depicted in Figure 14, embracing the optimal urban layout proposed in this study leads to an extension in the duration of thermal comfort. Consequently, upon scrutinizing all alternatives, it becomes apparent that roads aligned along the northeast-southwest axis, flanked by medium-sized buildings (with a H/W ratio of 1) extending in the northwest-southeast direction, present the most favorable thermal conditions.

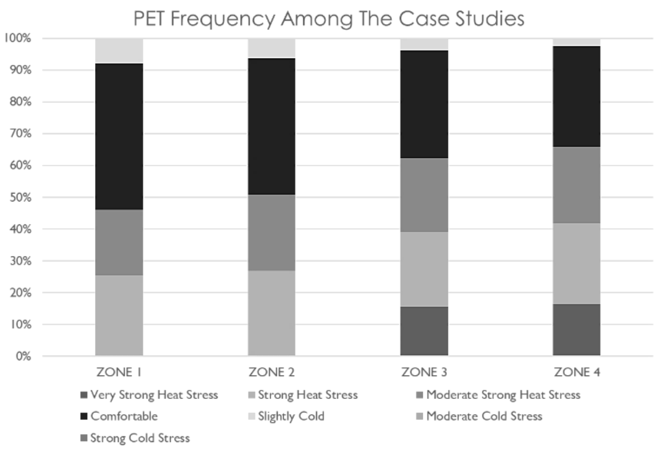

Fig. 14: PET frequency in selected zones

The research reveals that wind speed stands out as the primary factor affecting outdoor thermal comfort in this particular coastal area with humid subtropical climatic conditions. Following closely as the second most significant factor is the mean radiant temperature (H), representing exposure to solar radiation. Therefore, the considerable influence of road orientation and aspect ratio variables on Physiological Equivalent Temperature (PET) values is anticipated. Analyzing the PET data across different zones reveals varying thermal comfort and stress levels. Zones 1 and 2 exhibit similar patterns, with a significant proportion experiencing moderate to strong heat stress, indicating potentially uncomfortable conditions.

In contrast, Zones 3 and 4 demonstrate a more balanced distribution, with a notable presence of comfortable conditions alongside moderate heat stress. Interestingly, Zone 3 displays a higher prevalence of slightly cold conditions than the other zones, suggesting a more diverse thermal experience. These findings underscore the importance of considering localized variations in thermal comfort when designing urban environments, highlighting the need for targeted interventions to mitigate heat stress and promote comfort across different zones.

Table 3 outlines the relationship between urban design elements and the four crucial weather parameters in effective percentages. This measure quantifies the difference between the optimal and least favorable options for each street orientation, building typology, aspect ratio, and planting pattern design aspect. Notably, temperature and relative humidity are identified as the least impactful, suggesting that their values show limited variability depending on the city's structure.

Table 3. Impact Percentage of Design Factors on Climatic Components

Research Parameters	**Effective Percentage**				
	T_a	Wind Speed	T_{mrt}	Relative Humidity	PET
Street Direction	0.27	13.65	24.39	2.56	39.12
Building Typology	0.19	8.12	22.46	2.47	4.17
Enclosure	0.54	0.76	41.12	0.57	36.78
Tree Planting	0.39	48.17	15.37	3.12	17.69

The proposed physical characteristics of the urban area are defined by its thoughtful design elements aimed at enhancing thermal comfort and livability. Firstly, the predominant NE-SW axis-oriented road layout ensures the highest level of thermal comfort compared to alternative orientations, with a substantial improvement of 34.73%. Secondly, the linear arrangement of buildings along the northwest-southeast axis is preferred, offering a superior thermal environment compared to alternative building typologies. This configuration promotes a comfortable urban atmosphere. Thirdly, maintaining an aspect ratio of 1.5 for buildings oriented along the northeast-to-southwest axis on roadways is recommended, optimizing the balance between architectural design and thermal performance. Lastly, the strategic deployment of densely planted trees at a 5-meter spacing further contributes to thermal comfort, significantly reducing the Physiological Equivalent Temperature (PET) by up to 12.07%. These combined features create an urban environment with exceptional thermal comfort and sustainability, fostering a pleasant and inviting atmosphere for residents and visitors alike.

6.0 CONCLUSION

This study delves into the thermal performance of streets within the Narmak Neighbourhood in Tehran, specifically focusing on the prevalent urban configurations found in residential areas of Tehran's region 4. Employing a parametric approach, a comprehensive series of thermal comfort investigations were conducted to systematically evaluate the effect of various urban design factors on outdoor space thermal conditions. The results are presented in the context of key climatic factors, including air temperature, mean radiant temperature, wind speed (V), and Relative Humidity. Utilizing the Physiological Equivalent Temperature (PET) Comfort Index as the benchmark for comfort levels, the study meticulously examines the microclimate conditions within Narmak's urban canyon. The research aims to contribute to a comprehensive thermal comfort guide for urban development, emphasizing the significant influence of relevant design parameters. The findings underscore that optimizing design parameters has the potential to markedly enhance thermal comfort, ultimately contributing to creating a more pleasant outdoor environment. By incorporating these urban design guidelines, planners and designers can create more comfortable and livable urban environments that prioritize outdoor thermal comfort and mitigate the adverse effects of heat stress. Here are the urban design guidelines provided from the research output:

1- Urban Street Direction

1-a) Prioritising NE-SW Street Orientation: Given its superior performance in providing thermal comfort, urban design should prioritize the orientation of streets along the NE-SW axis. This orientation creates a thermally comfortable environment for outdoor users, particularly during peak heat hours. Designing streets in this direction can significantly improve outdoor comfort levels and reduce the risk of heat stress.

1-b Considering North-South Orientation: While less favorable than NE-SW orientation, North-South street orientation emerges as the second most pivotal priority for enhancing outdoor thermal comfort. Designers should consider incorporating this orientation where feasible to provide thermal comfort for outdoor spaces throughout the day.

1-c) Mitigate Heat Stress in Less Favorable Orientations: For orientations such as northwest-southeast and east-west, where moderate to increased heat stress is experienced, urban design interventions are essential to mitigate thermal discomfort. Strategies include increasing shade effects, optimizing building design to provide shade and ventilation, and implementing green infrastructure such as strategic tree planting.

1-d) Optimise Wind Flow: Wind speed plays a vital role in outdoor thermal comfort. Designing streets and urban spaces to facilitate optimal wind flow, particularly in favorable orientations like NE-SW, can enhance thermal comfort. Strategies include incorporating open spaces, creating wind corridors, and minimizing obstructions to wind flow.

1-e) Consider Microclimatic Factors: Understanding microclimatic factors such as mean radiant temperature and wind speed variations across different orientations is crucial in urban design. Designers should consider these factors in site planning, building placement, and landscape design to create microclimates that optimize outdoor thermal comfort.

2- Building Classification

2-a) Preference for Northwest-Southeast Building Arrangement: The linear arrangement of buildings along the northwest-southeast axis is identified as the more comfortable option for outdoor thermal comfort. Urban planning solutions should prioritize this orientation to create a thermal environment of superior quality.

2-b) Avoidance of Northeast-Southwest Building Arrangement: The finding suggests avoiding the incorporation of a linear building typology extending in the northeast-southwest direction. This arrangement fails to enhance thermal conditions notably and may lead to less comfortable outdoor environments.

2-c) Consistency in Building Typology Design: Despite variations in building typologies, such as singular and extended linear configurations, the orientation and aspect ratio of the design elements remain consistent. Urban planners should maintain this consistency to ensure minimal disparities in comfort conditions based on current favorable thermal performance findings.

2-d) Consideration of Wind Speeds: Urban design should consider the impact of building configurations on wind speeds. The investigation highlights that maximum wind speeds are observed in a linear building configuration extending in the northeast-southwest direction. Designers should leverage this insight to optimize wind flow and enhance outdoor comfort.

2-e) Monitoring Climatic Parameters: While the investigation did not reveal significant changes in other climatic parameters, such as relative humidity and mean radiant temperature, ongoing monitoring of these factors is crucial in urban planning. Designers should remain vigilant to variations and adapt design strategies to maintain optimal outdoor thermal comfort.

3- Enclosure

3-a) Optimal Aspect Ratio for Thermal Comfort: Adjustments to the enclosure aspect ratio significantly delineate a thermally comfortable urban environment. Increasing the aspect ratio by 0.5, within certain limits, reduces maximum mean radiant temperature and Physiological Equivalent Temperature (PET) values, thus enhancing comfort. However, caution should be exercised not to exceed an aspect ratio of one in coastal areas with elevated wind speeds, as this can shift the comfort range and result in moderately cooler road conditions, particularly in the late afternoon.

3-b) Aspect Ratio and Shading: Increasing the aspect ratio contributes to a higher proportion of horizontal surface shading, which is crucial for achieving satisfactory comfort levels, especially during peak heat hours from 10 am to 3 pm. Designers should consider augmenting the aspect ratio to enhance shading and mitigate heat load, improving thermal comfort in urban environments.

3-c) Effect on Mean Radiant Temperature: Augmenting the aspect ratio correlates with a decline in the average radiant temperature, as indicated by the Mean Radiant Temperature Index (MRI) parameter. For every 0.5 increase in the ratio value, there is a corresponding decrease in the MRI parameter, highlighting the effectiveness of this strategy in reducing thermal discomfort.

3-d) Maintaining Wind Speed and Humidity Levels: No significant alterations were observed in wind speed or humidity levels during adjustments to the aspect ratio. Urban designers can thus optimize the aspect ratio to enhance thermal comfort without compromising other climatic factors.

4- Vegetation Pattern

4-a) Implementation of Vegetation and Tree Planting: Introducing vegetation and planting trees along urban streets is an effective strategy for improving thermal comfort, especially in areas with suboptimal orientation and low-rise buildings. This approach, particularly with densely planted trees spaced at 5 meters, can significantly reduce Physiological Equivalent Temperature (PET) values by up to 12.07%. However, even with a sparser planting pattern, a notable reduction in PET levels, up to 7.83%, can still be achieved.

4-b) Optimal Planting Patterns: Urban planners should carefully consider the planting pattern of trees to maximise the reduction in PET values. Dense planting patterns are more effective in mitigating thermal discomfort than sparse arrangements. Thus, prioritising densely planted trees, especially in areas with challenging thermal environments, can yield greater benefits for improving outdoor comfort.

4-c) Impact on Relative Humidity: The introduction of greenery and trees contributes to an increase in relative humidity by a maximum of 1.1%. This increase in humidity enhances thermal comfort in urban streets, especially during hot and dry conditions, by creating a more pleasant microclimate.

4-d) Management of Plantations: Consolidating and strategically removing plantations can optimise thermal conditions. This management approach can lead to a reduction in the average mean radiant temperature, thereby enhancing overall comfort levels for pedestrians and outdoor users.

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