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Assessing Pedestrian Thermal Comfort to Improve Walkability in the Urban Tropical Environment of Nagpur City

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KEYWORDS

Walkability
Sustainable Transportation
Microclimate
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ABSTRACT

Walking can be an efficient and sustainable mode of transportation for "last mile" connectivity. However, the willingness to walk largely depends on the availability of infrastructure, safety, and comfort. Improving thermal comfort on streets connected to transit stations is crucial for encouraging walking and public transit use. This study assesses seasonal and spatiotemporal variations in pedestrian thermal comfort (PTC) on an N-S-oriented street in Nagpur (India). Thermal walk surveys simultaneously monitored environmental conditions and human thermal perception (thermal sensation vote- TSV). The findings revealed that urban geometry significantly influences PTC and TSV, and the level of influence varied spatiotemporally in both seasons. This study shows the relationship between urban street geometry, microclimate, and PTC, emphasizing the necessity of a multidimensional assessment approach.

Introduction

In recent years, urbanization has resulted in significant changes in land use, characterized by dense built-up areas, extensive pavement, and less vegetation (Zhou & Chen, 2018). These changes have led to adverse environmental and local microclimate consequences, such as the Urban Heat Island effect (UHI), which increases heat stress (Kotharkar et al., 2018; Oke, 1988). The increasing heat stress significantly impacts the quality of outdoor places by decreasing comfort (Nikolopoulou & Lykoudis, 2006; Yahia et al., 2018). The uncomfortable outdoor conditions discourage people from choosing sustainable last-mile connectivity options such as walking and cycling (Arif & Yola, 2020). Instead, many choose motorized vehicles, which increase carbon emissions, air pollution, and traffic congestion. Improving walkability to address these issues and promoting sustainable transportation options is crucial (Chidambara, 2019; Shamsuddin et al., 2012). There are several barriers to walkability, such as the availability of pedestrian infrastructure, accessibility, connectivity, safety, and comfort. Pedestrians in tropical climates face challenges due to extreme heat, humidity, and prolonged sun exposure, which makes walking less feasible (Deevi & Chundeli, 2020). Improving the thermal comfort on streets that connect to transit stations is essential to promote walking and public transit use.

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Literature Review

Thermal comfort refers to the degree of satisfaction and well-being experienced by individuals while walking or moving through outdoor spaces (ASHRAE, 2023; Vasilikou & Nikolopoulou, 2020). The thermal environment influences how individuals perceive and experience outdoor space (Nikolopoulou et al., 2001). It encompasses various physical, psychological, and environmental factors that influence a person's comfort (Chen et al., 2012; Lau et al., 2019; Nikolopoulou & Lykoudis, 2006; Vasilikou & Nikolopoulou, 2013).

Pedestrian thermal comfort (PTC) is influenced by microclimatic parameters such as air temperature, humidity, and wind speed, etc. The microclimate at the street level is influenced by urban geometry, which includes factors such as aspect ratio, sky view factor, and street orientation (Ahmadi Venhari et al., 2019; Jamei & Rajagopalan, 2015; Krüger, 2011). The street orientation and aspect ratio of buildings determine solar exposure and shadow patterns, affecting surface and air temperature variations throughout the day (Baghaeipoor & Nasrollahi, 2019; Cliff Moughtin, 2003; Svensson, 2004). In additional, the density of buildings can influence wind speed, leading to changes in thermal conditions. The presence of trees helps regulate temperature by providing shade and transpiration (Kim & Brown, 2022; Kotharkar et al., 2023; Mahmoud et al., 2021).

Previous studies have shown that a comprehensive understanding of PTC requires an assessment of the thermal environment both objectively and subjectively (Deevi & Chundeli, 2020; Lau et al., 2019; Peng et al., 2022; Vasilikou & Nikolopoulou, 2013). The objective assessment of the thermal environment involves quantifying thermal comfort based on the heat balance of the human body and its heat exchange with the surrounding environment. Various methods and indices have been developed to evaluate PTC. These indices include the predicted mean vote (PMV) (Van Hoof, 2008), the universal thermal climate index (UTCI) (Błazejczyk et al., 2013), and physiologically equivalent temperature (PET) (Mayer & Höppe, 1987). The PMV index evaluates the thermal sensation of people considering microclimatic parameters. The index is widely accepted but can be overly sensitive to wind speed variations, limiting its suitability for tropical hot and dry climates. The UTCI index is a widely known index that uses a simple equation to evaluate thermal comfort based on microclimatic variables. However, it does not consider the physiological aspects of humans, such as metabolic rate and clothing. The current study uses the modified Physiologically Equivalent Temperature Index (mPET) (Chen et al., 2018), which is a modified version of the PET index. The PET is the physiologically equivalent temperature at any given place (outdoors or indoors). It is equivalent to the air temperature at which the human body's heat balance is maintained, with core and skin temperatures equal to those under the assessed conditions. The mPET enhances accuracy by considering thermo-physiological parameters of the human body and climatic factors. Unlike other indices, mPET incorporates a multi-node heat transport model and a self-adapting multi-layer clothing model, providing a more realistic analysis of the impact of climate on humans (Chen et al., 2020; Pecelj et al., 2021).

Subjective assessment of the thermal environment involves the analysis of thermal sensation through people's perception. Thermal sensation is a specific aspect of PTC; it pertains to individuals' immediate perception of the microclimate in their surroundings (Nikolopoulou & Lykoudis, 2006). The "thermal walk" method helps analyze the thermal sensation (Vasilikou & Nikolopoulou, 2013). Thermal walks help to understand how people perceive outdoor environmental conditions in urban settings. During a thermal walk, participants walk through various locations within a specific area, carefully evaluating the thermal conditions at each location. This requires close observation and analysis of the unique thermal attributes that characterize different urban environments.

Research Gap

In India, walkability studies have been conducted by several researchers and authorities, such as the Evangelical Social Action Forum conducted a walkability survey in Nagpur and Kochi (ESAF, 2017), while the Clean air initiative organization conducted surveys in Pune, Bangalore, Bhubaneshwar, Chennai, Rajkot, Surat, Kota, and Indore (Clean air initiative for Asian cities center, 2011). The survey used the Global Walkability Index methodology from the World Bank, involving field surveys, pedestrian preferences, and government policy assessments. These studies focused on walkability from the infrastructure and safety perspective and did not include thermal comfort.

Several studies have been conducted in different cities in India that assess outdoor thermal comfort and the impact of heat stress on people using outdoor environments. Most studies have focused on a neighborhood scale, public parks, etc. (Anupriya & Rubeena, 2023; Kotharkar et al., 2024; Kumar et al., 2022; Salal et al., 2021). Some studies have considered assessing thermal comfort on the street level. However, in these studies, the streets are analyzed as singular locations rather than on the microscale of individual streets (Banerjee et al., 2022; Kotharkar et al., 2019; Manavvi & Rajasekar, 2020). Very few studies have assessed PTC on sidewalks and the impact of urban geometry and microclimate on pedestrians while walking (Chidambaranath & Bitossi, 2018; Deevi & Chundeli, 2020).

Aim and Objective

This study aims to assess and enhance pedestrian walkability on the street level by evaluating PTC on the street that fulfills walkability parameters, using objective (mPET index) and subjective (TSV) methods. The study aims to achieve three objectives: 1) compare dynamic changes in pedestrians' thermal sensation and comfort concerning variations in urban geometry, 2) identify significant variations in thermal stress with microclimatic factors, and 3) determine the neutral value of mPET, serving as a benchmark for thermal stress in Nagpur city. This pilot study introduces a methodological framework that can be employed in future studies.

Research Area

The study was conducted in Nagpur, Maharashtra, India (21.1458° N and 79.0882° E) (Fig.1). Nagpur has a tropical savanna climate (Aw), with hot and dry summers and cool and dry winters, as per the Köppen-Geiger classification (Kottek et al., 2006). The city is developing as a fast-growing metro city and has a status as a smart city under the Smart City Mission India (India Smart City Mission, 2015). The Nagpur Metro Rail Project comprises two corridors, North–South measuring 19.6 km in length with 17 stations, and East–West measuring 18.5 km in length with 19 stations (Nagpur Metro Rail Corporation, 2023). The city's public transportation connectivity highlights the need to improve walkability around transportation hubs. As per the MOUD walkability index, the city has a walkability index of 0.65, which is above the national minimum average (Ministry of Urban Development, 2008). However, the city's tropical climate encounters significant temperature variations throughout the year, with winters bringing minimum temperatures of 12°C and summers seeing temperatures soaring up to 48°C, often accompanied by heatwaves (Katpatal et al., 2008; Laskar et al., 2016; Surawar & Kotharkar, 2017). This can result in uncomfortable outdoor environments and potential discomfort for pedestrians during summer and heatwave conditions.

The street was selected based on walkability parameters such as mixed land use typology, connectivity to the metro, and availability of pedestrian sidewalks on both sides of the streets. The New Shukrawari Road (Fig 2) is located at one of the prominent CBDs in Nagpur. The nearest metro station to this street is the Agrasen Square metro station, located on the north side of the street. The selected stretch of the street is approximately 1 km long and runs north-south. It is lined with buildings of varying heights, ranging from 1 to 5 floors, with various stores, restaurants, bars, shopping centers, offices, and residential spaces. The street is designed with distinct zones for vehicles and pedestrians. The vehicular zone comprises four lanes, and 1.5 mt wide sidewalks are on both sides of the street, designated as the Eastern and Western Sidewalks.

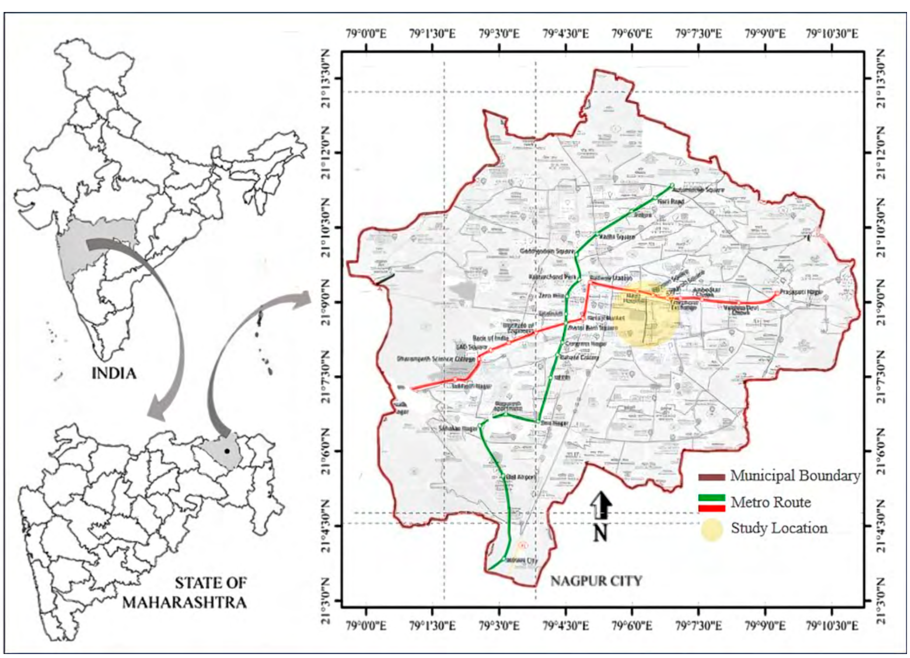

Figure 1. Location of Nagpur City and the study area

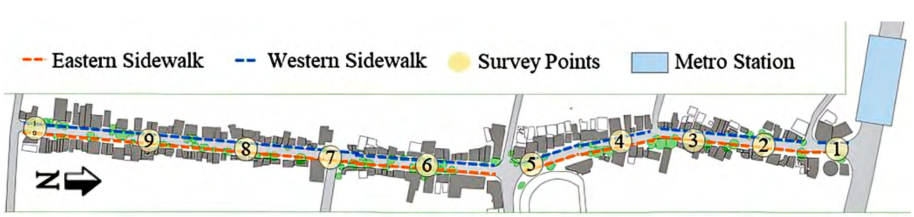

Figure 2. Digitized image of the New Sukrawari Road

Methodology

The study methodology is divided in 4 phases (Fig.3). In the first phase, the selected street was digitized using Arc-GIS software through satellite overviewing to map buildings, streets, vegetation, and sidewalks (Fig.2). The building and vegetation characteristics of the street are evaluated in Arc-GIS by calculating the Building Surface Area Fraction (BSF) (Eq.1), which shows a portion of the ground surface covered with a building footprint, and the Vegetation Density ratio (VDR) (Eq.2), which shows a portion of the ground surface covered with vegetation. These parameters range from 0 to 1. It provides the urban geometry characteristics of the entire street. The calculated BSF for this street is 0.65, and the VDR is 0.40.

$$BSF = L_B / L_s \tag{1}$$

$$VDR = A_V / A_s \tag{2}$$

Where,

- L_B =Total length of building surface facing the street
- L_s = Total length of the sidewalk
- A_V = Total area of vegetation
- A_s = Total area of the street

In second phase, a longitudinal thermal walk survey was conducted to collect microclimate, urban geometry, and pedestrian perception data. The street was divided into the 100m grid; thus, 10 survey points were studied (Fig.2). These points exhibit unequal building heights with varied aspect ratios and SVF to assess different scenarios of thermal conditions. The points on the east side of the street are named East 1, East 2, etc, whereas the points on the west side are West 1, West 2, etc. The survey campaign was conducted in the summer of 2022 (May 22, 2022) and winter 2023 (February 19, 2023) to understand seasonal variations in PTC. In each season, the microclimate and perception data were collected at three different times: 9:00 am -10:00 am, 11:30 am – 12:30 pm, and 5:00 pm – 6:00 pm. These particular time durations were studied because the maximum pedestrian movement around metro stations was observed during morning and evening hours. In contrast, the afternoon hours were studied to understand pedestrian behavior during peak solar radiation and higher radiant heat exposure. To eliminate temporal variations in background meteorological conditions, a survey route was followed to collect data on the same side first and then move to the opposite side (Fig. 3- Representative longitudinal survey route).

The initial data collection process encompassed conducting on-site observations at every survey point to document the urban geometry parameters of the location and measure climatic parameters along with the thermal perception of the participants (Fig.3). The climatic parameters include air temperature (Ta), surface temperature (Ts), relative humidity (RH), and wind speed (Ws). Following the ASHRAE-55 protocol, measurements were taken at a height of 1.2 m from the ground (ASHRAE, 2023; ASHRAE, 2013), using the MS 6252B Digital Anemometer for Ta, RH, and Ws measurements, while the surface temperature was measured using a Laser IR Thermometer-thermal gun. These

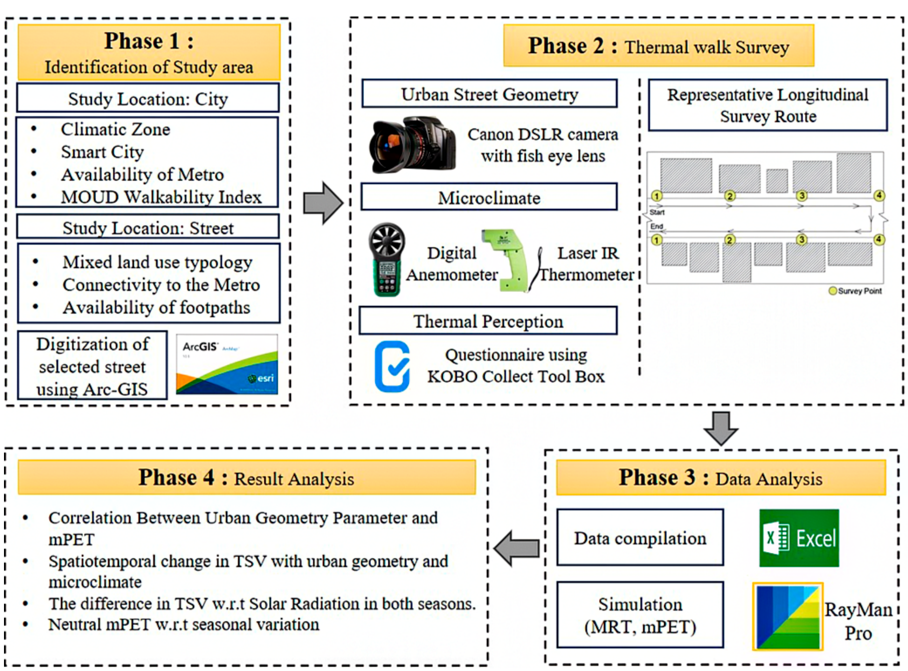

Figure 3. Methodology flow chart

instruments were calibrated and tested in the outdoor environment for their sensitivity before being used for field surveys. The response time of these instruments is 1 sec. The urban geometry parameters include the aspect ratio (AR) and sky view factor (SVF). AR was calculated by measuring street width and building height using Google Earth and Street View, respectively, and a Nikon DSLR camera with a fisheye lens was employed to capture SVF images.

For the perception survey, the questionnaire followed the ASHRAE outdoor thermal comfort protocol. The questionnaire was divided into two parts, first about personal information and second about thermal sensation. The second part of the questionnaire included three questions, and the options were given on a Likert scale. The first set of questions concerns the thermal perception of microclimatic parameters (5-point scale). The second set of questions includes thermal preference for microclimatic parameters (3-point scale); in microclimatic conditions, people would prefer to walk for maximum duration without feeling discomfort. The third set of questions includes the thermal sensation vote (ASHRAE 9-point scale) (Fig.4).

Perception survey data were collected using the KOBO Collect App. It is an Android-based app that helps to record the data initially in the app and then on a cloud server, which makes it easy to process and analyze the recorded data. The perception survey was conducted through a closed group survey during both seasons to capture the two climatic conditions. Six males and nine females aged between 19-31 years participated in the survey. The same people were asked to participate in both seasons to avoid disparity.

For every walk, the participants were asked to be present at the survey location and stand under shade for 15 minutes before the survey time to acclimatize to the microclimate. Each side of the street (approximately 1 km) The thermal walks were conducted in a guided survey manner; thus, all participants walked with a researcher who guided them to the location. The participants were asked to stand for 2 minutes at every location to record their responses. The researcher simultaneously recorded the microclimate and urban geometry data. It took approximately 30 minutes to complete a survey on one side of the street. 90 forms were collected for both sides of the street in a day, leading to a total data sample of 900 for each season, as there were ten survey points on either side of the street.

Part 1: Personal Information and Thermal History

Gender: Male Female Other
Age: ≥20 20-30 30-40 40-50 50 and above
Height: __ cm Weight: __kg
Clothing:

Part 2: Thermal sensation

1. **Standing in at this moment**

Under sunlight Building shade canopy shade Tree shade

2. **At This precise moment, do you find the following**

Humidity:	Dry	Slightly Dry	Neutral	Slightly Humid	Humid
Wind speed:	Less Windy	Slightly Less Windy	Neutral	Slightly Windy	Windy
Sunlight:	Soothing	Slightly Soothing	Neutral	Slightly Harsh	Harsh

3. **How would you prefer the following?**

Humidity:	Less Humid	Neutral	More Humid
Wind speed:	Less Wind	Neutral	More Wind
Sunlight:	Lower	Neutral	Higher

4. **How do you feel at this precise moment?**

Very	Cold Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot	Very Hot
(-4)	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)	(4)

Figure 4. Thermal walk questionnaire

In the third phase, microclimate data collected were analyzed using the RayMan Pro tool to evaluate the mean radiant temperature (MRT) and the thermal comfort in-

Figure 5. Thermal walk survey during winter and summer

dex, mPET. The RayMan Pro tool was also used to evaluate the actual solar radiations, considering the SVF, day, time, and geographical location for calculation. The perception data was compiled and evaluated in Microsoft Excel. In the fourth phase, Pearson's correlation was used to understand the impact of urban geometry parameters on the thermal comfort index. For this purpose, the SVF values were correlated with the mPET values, as the SVF represents all the features of urban geometry, including buildings, vegetation, and other built-up structures. The neutral value of mPET was derived using a regression equation between TSV and mPET values. A one-way ANOVA test was used to check the variation in TSV concerning microclimatic parameters.

Results

Urban Geometry and Microclimate Measurements

The field data observations show that the urban geometry of the studied locations is distinct (fig. 6), and there are considerable spatiotemporal variations in meteorological conditions along the walking routes on both sides of the road in two different seasons. As per urban geometry observations, for the eastern side, the ARmax observed is 1.3 at East 1 because there is a multistory building adjacent to the road, and the ARmin is 0 at East 5 because there is no building adjacent to the road. The SVF varied between the maximum value of 0.78 at East 5 due to the absence of a tree and minimum obstruction from built forms; the minimum value of SVF was 0.25 at East 6 due to a wide canopy tree. On the western side of the street, ARmax is observed at 0.80 at West1 as a multistory building adjacent to the road, and ARmin at 0.20 at West 2 and 3 as a single-story building. The SVF varied between the maximum value of 0.66 at west 3,4 due to the absence of a tree and minimum obstruction from built forms; the minimum value of SVF was 0.18 at west 6 due to a wide canopy tree.

On the N– S orientation street, the variation pattern of microclimatic parameters was observed to be similar in both seasons (fig. 7 and 8). On the eastern side, in the morning duration of 9:00–10:00 am, due to low solar radiation, Ta, Ts, and MRT were observed to be minimum, and RH was maximum. At 11:30 a.m.–12:30 p.m., the duration of RH was observed to decrease, and temperature values were increasing. The temperature values decrease in the evening, 5:00–6:00 p.m., and the RH increases. On the west side of the street, in the morning of 9:00–10:00 a.m., the Ta, Ts, and MRT were observed to be higher than those on the eastern side as this side receives direct solar radiation, and the temperature values were observed to be maximum during the afternoon period of 11:30–12:30 pm. The minimum temperature values were recorded in the evening from 5:00 to 6:00 p.m. The Ws were observed to be dynamic irrespective of the street side throughout the day. In the winter season (Fig. 7), the maximum and minimum solar radiation on the eastern sidewalk was 933.8 W/m² and 22.5 W/m², respectively. On the western sidewalk, it was 938.2 W/m² and 21 W/m². The maximum and minimum Ta values on the eastern sidewalk were 34°C and 26°C, respectively, and on the western sidewalk, the Ta values were 33°C and 25.6°C, respectively. The maximum and minimum RH on the eastern sidewalk was 47.6% and 25%, respectively, and on the western sidewalk, the RH was 46.3% and 26%, respectively. In the summer

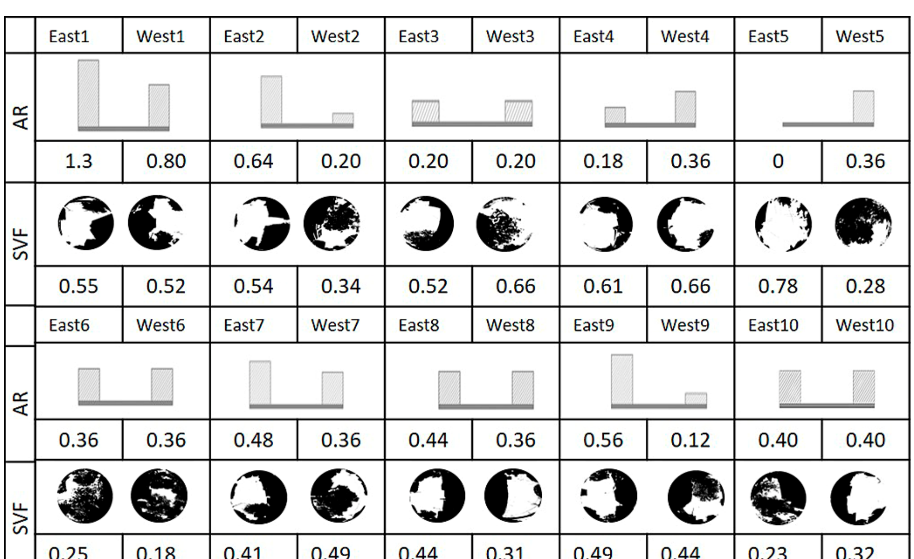

Figure 6. Survey locations with their respective aspect ratios and sky view factors

season (Fig.8), the maximum and minimum solar radiation on the eastern sidewalk was 1012 W/m² and 64.9 W/m², respectively. On the western sidewalk, it was 1015.3 W/m² and 44.7 W/m². The maximum and minimum Ta on the eastern sidewalk were 43.5°C and 36.7°C, respectively, and on the western sidewalk, Ta was 43.5°C and 37.5°C, respectively. The maximum and minimum RHs on the eastern sidewalk were 33.6% and 24%, respectively; on the western sidewalk, the RHs were 34.5% and 23.8%, respectively.

Thermal walks

From the responses of people's perception of individual microclimatic factors, it was observed that most of the participants preferred to walk on sidewalks shaded by buildings and vegetation irrespective of the season. The level of solar radiation and Ws largely influenced thermal perception (TSV). From simultaneous wind perception and Ws measurement, it was observed that participants voted Ws of more than 1m/s as neutral to windy. In winter, the mean TSV (mTSV) was between cool (-2) and slight-

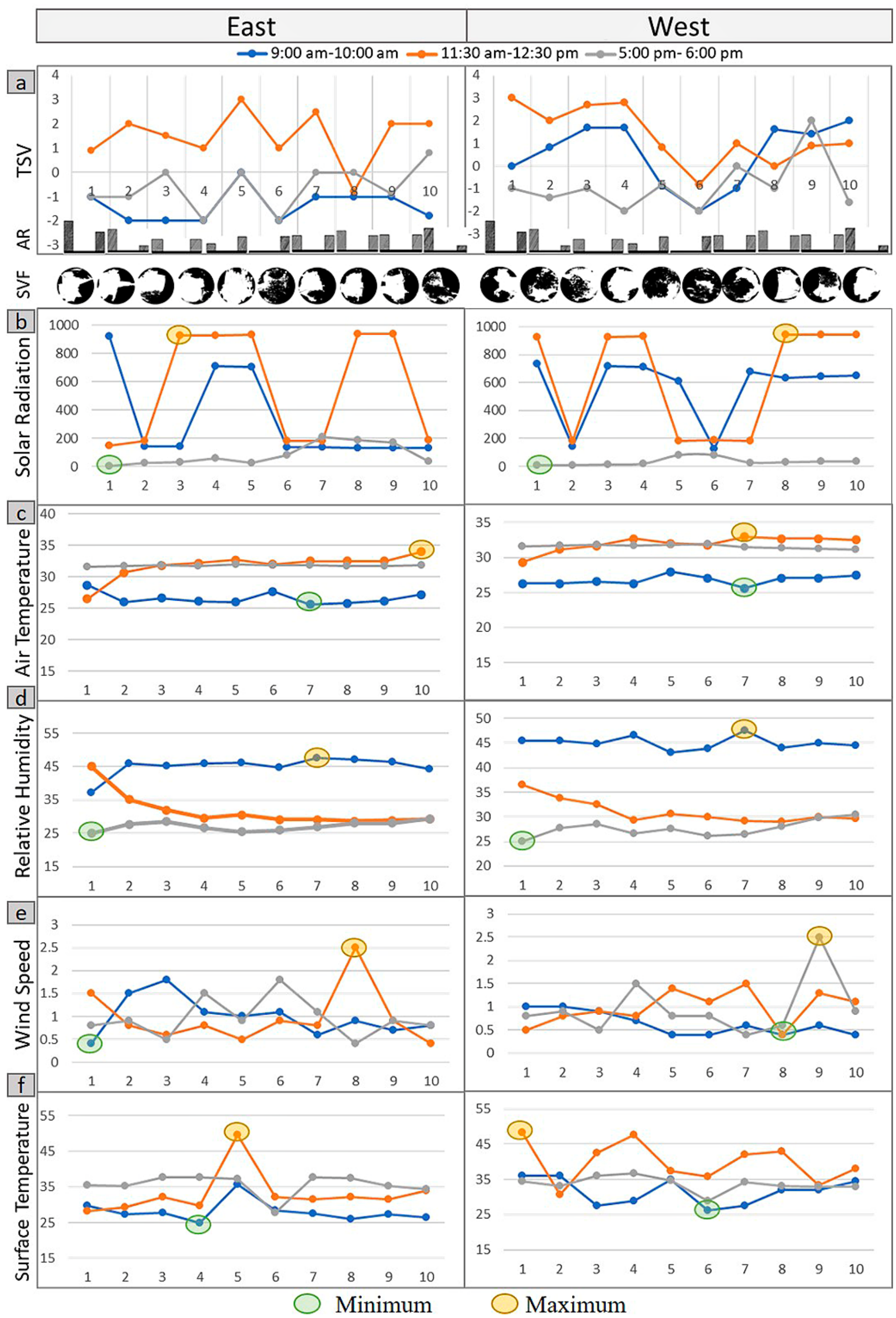

Figure 7. Diagram of factors connecting TSV, urban geometry, and microclimatic factors in Winter. Graph (a) shows variation in TSV at the studied time durations with AR and SVF; graphs (b),(c),(d), and (f) show the variation in microclimatic parameters

ly cool (-1) under shade, whereas slightly warm (2) under sunlight (Fig.7). Participants' Ws perception was between neutral to slightly windy in the morning (9:00 am – 10:00 am) and evening (5:00 pm – 6:00 pm). They preferred slightly less Ws as it made them feel a cool thermal sensation. In the afternoon (11:30 am - 12:30 pm), wind speed perception was between slightly less wind and neutral, and Ws preference was between neutral and more wind as thermal sensation improved with the wind. In Summer, the mTSV was between neutral and warm (2) under shade. In contrast, under sunlight, it was between warm (2) and very hot (4) (Fig.8). In the morning (9:00 am - 10:00 am) and evening (5:00 pm - 6:00 pm), the TSV was between neutral (0) under shade and warm (2) under direct sunlight. Participants' wind preference was neutral to more wind. In the afternoon (11:30 am - 12:30 pm), the TSV was between warm (2) and very hot(4), and participants' Ws preference was between less wind and neutral; the TSV in the afternoon increased because of low RH.

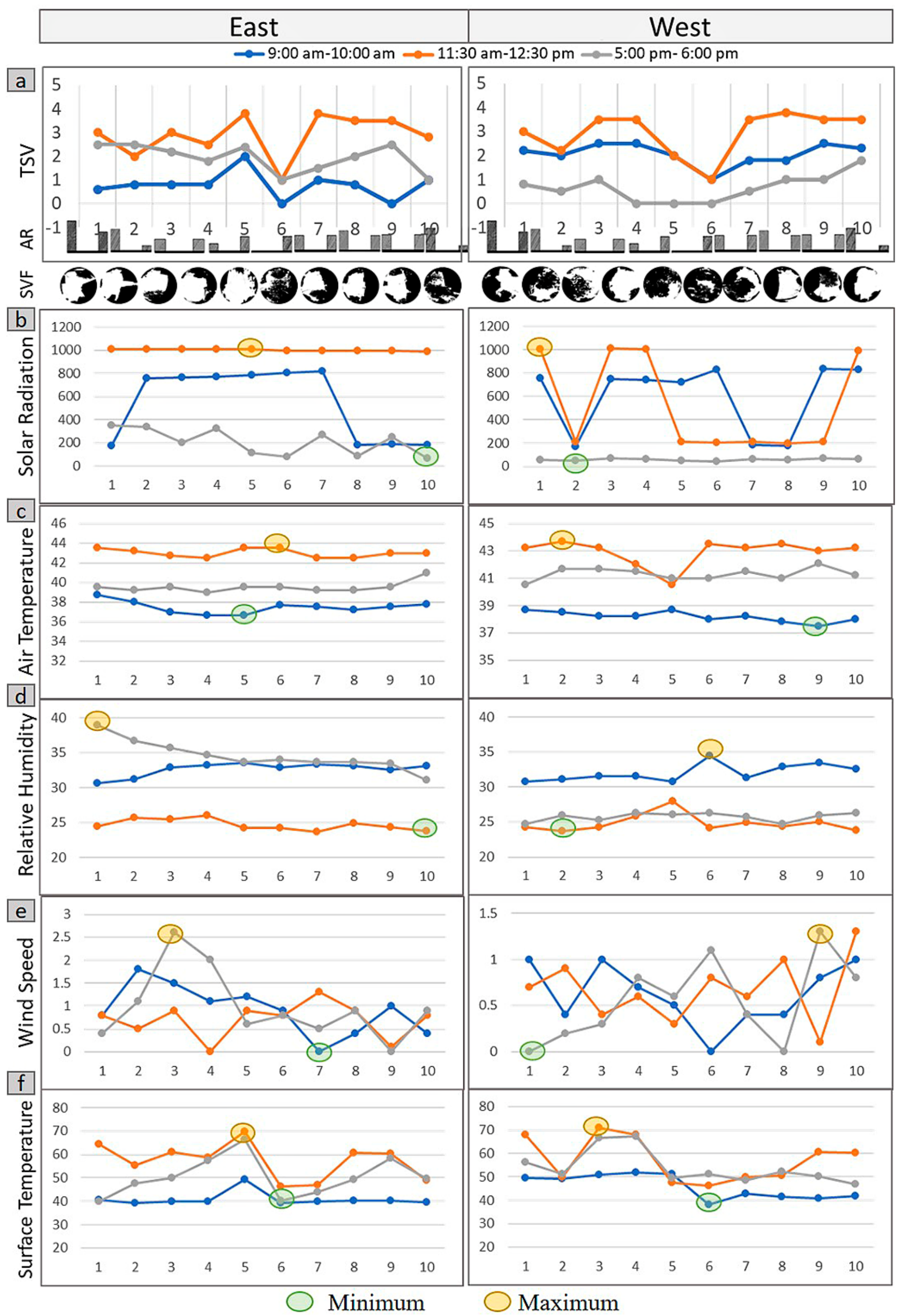

Figure 8. Diagram of factors connecting TSV, urban geometry, and microclimatic factors in Summer. Graph (a) shows variation in TSV at the studied time durations with AR and SVF; graphs (b),(c),(d), and (f) show the variation in microclimatic parameters

Change in TSV with Microclimate and Urban Geometry

Microclimate parameters play an essential role in outdoor thermal sensation. As discussed in thermal walk observations, the increase in Ta and solar radiation, outdoor thermal sensation increases, whereas it decreases with Ws and RH. The changes in TSV with respect to urban geometry and microclimatic parameters throughout the day are represented in Fig (7) for winter and Fig (8) for summer. This representation approach allows to compare the participants' thermal experiences with the measured environmental conditions.

In both the seasons, the TSV on eastern sidewalk in morning was low compared to the western sidewalk due to availability of shade on eastern sidewalk. In the afternoon the points with minimum SVF have low TSV. Whereas in the evening, during winter season, both sidewalks have almost similar TSV, due to low intensity of solar radiation and wind speed. The point 6 on both sidewalks have wide canopy tree thus the TSV at this point is low throughout the day, whereas the location East 5 has maximum SVF thus the TSV is high throughout the day in both seasons. The overall observations show that individuals exposed to direct sunlight tend to overestimate their thermal comfort, irrespective of the season, whereas those in shaded areas often underestimate it.

Table 1. Results of ANOVA using TSV as a covariate

One - way ANOVA							
	Source of variation	SS	df	MS	F	P-value	F crit
Summer	Between Groups	22139294	1	22139294	288.35	1.55E-49	3.86
	Within Groups	32016044	410	76777.08			
Winter	Between Groups	3026638	1	3026638	43.38	1.38E-10	3.86
	Within Groups	28603493	410	69764.62			

A one-way ANOVA test was performed to check if the TSV varies equally with solar radiation in both seasons. In this test, solar radiation is considered the independent variable, and TSV is the dependent variable. The level of impact of solar radiation on TSV is determined by comparing the F-value, F-crit value, and P-value. The results of the one-way ANOVA test showed that in both seasons, the TSV varies significantly with the level of solar radiation (Table 1). The difference between the F-value and the F-crit value in summer is greater than that in winter, indicating that people prefer to walk under shade for a in summer to feel comfortable. This indicates the importance of shading in the PTC.

Effect of Urban Geometry on mPET

The correlation analysis of urban geometry parameters, SVF, and mPET showed that during both seasons, the influence of urban geometry on thermal comfort varied with time and for the side of the street. During morning hours (9:00 am - 10:00 am) in both seasons, the east side of the street with buildings adjacent to it is not exposed to solar radiation. As a result, the MRT and mPET are at a minimum on this side. Conversely, most of the survey points expose the west side of the street to solar radiation, leading to maximum MRT and mPET values. Thus, the correlation between SVF and mPET is strong on the east side (R^2 value: 0.80 for summer and 0.65 for winter), whereas it is weak on the west side (R^2 value: 0.23 for summer and 0.24 for winter) (Fig 9,10).

In the afternoon (11:30 am - 12:30 pm), during both seasons, both sides of the street with high SVF are exposed to solar radiation, resulting in similar microclimates. Points with the presence of a tree or any other artificial shading result in comparatively minimum MRT and mPET. Survey point East 5 has the maximum SVF value, leading to the maximum MRT and mPET values. On the other hand, survey points East 6 and West 6 have the minimum SVF, resulting in minimum MRT and mPET throughout the day. On the studied street, the east side has the presence of trees at multiple survey points; thus, the correlation on the east side is strong (R^2 value: 0.90 for summer and 0.92 for

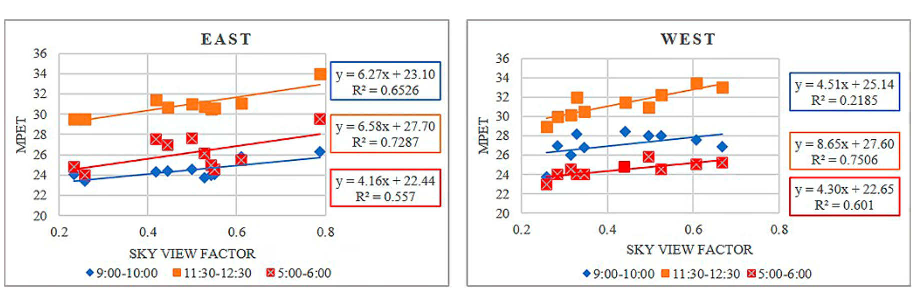

Figure 9. Correlation between SVF and mPET during the Winter

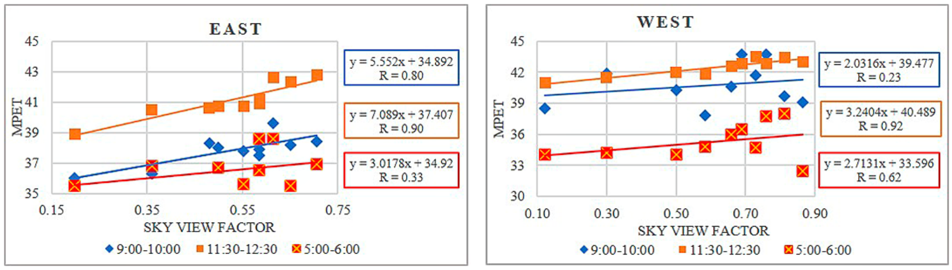

Figure 10. Correlation between SVF and mPET during the Summer

winter) compared to the west side (R^2 value:0.72 for summer and 0.75 for winter) (Fig 9,10).

In the summer season, during the evening (5:00 pm - 6:00 pm), the west side of the street has adjacent buildings blocking solar radiation, while the eastern side remains exposed to it. Therefore, the western side experiences minimum MRT and mPET compared with the eastern side. Thus, the correlation on the west side is strong (R^2 value: 0.62) (Fig 9), whereas on the east side, it is weak (R^2 value: 0.33) (Fig 10). In the winter season, as the sun's azimuth angle is lower, the buildings on the west side block solar radiation for both sides of the street, resulting in minimum mPET values for both sides. Thus, there is no significant difference in the correlation for both sides of the street (R^2 value: 0.55 for the east and 0.60 for the west) (Fig 9,10).

Change in TSV with mPET

The correlation between TSV and mPET can help establish a relationship between the perceived thermal comfort of individuals and the quantified thermal conditions based on mPET. The correlation indicates that people's thermal sensation votes are in agreement with the calculated mPET values (Fig.11).

Although TSV and mPET correlate positively, it is important to evaluate if the physiological stress associated with the mPET index is the same as the actual thermal sensation experienced by people. Thus, the neutral PET was determined using mTSV = 0 in the regression equation. The regression equation for the street in both seasons is described below:

$$y = 0.42x - 11.87 \text{ (East\_Winter)} \quad (3)$$

$$y = 0.38x - 10.74 \text{ (West\_Winter)} \quad (4)$$

$$y = 0.28x - 8.90 \text{ (East\_Summer)} \quad (5)$$

$$y = 0.39x - 12.67 \text{ (West\_Summer)} \quad (6)$$

Where,

- y = mTSV
- x = mPET

The results show that for winter, the neutral mPET values for the Eastern sidewalk is 28.1°C and for the western sidewalk is 27.9°C, respectively. Therefore, the average neutral mPET value for the winter is 28°C. Similarly, for summer, the neutral mPET values for the eastern and western sidewalk are 31.7°C and 32.4°C, respectively. Therefore, the average neutral mPET value for the summer is 32°C. According to the mPET index, the neutral thermal stress varies between 26-30°C (Chen et al., 2018). Whereas for Nagpur city, it is 32°C in summer. This shows an increase in adaptive tolerance to higher temperatures in the summer season, that is, the ability of individuals to adapt and adjust their comfort perceptions and responses based on changing environmental conditions.

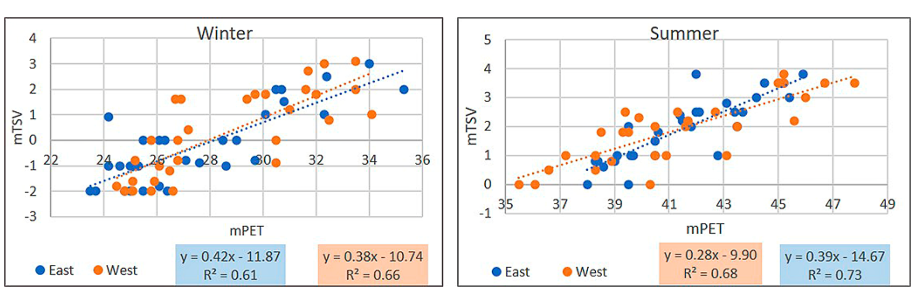

Figure 11. Correlation between mTSV and mPET for winter and summer

Discussion

The study was conducted in Nagpur city, which has a tropical Savannah climate. This study analyzes the seasonal and spatio-temporal behaviors of PTCs on an oriented street as a pilot study in the summer of 2022 and winter of 2023. The results show that urban geometry has an essential effect on the urban microclimate. Urban geometry governs the level of solar radiation, which influences ground Ts and Ta directly above it. The N– S orientation of the street is parallel to the solar path; thus, the building adjacent to the street effectively blocks solar radiation throughout the day and provides shade for pedestrians on the sidewalk. The correlation between SVF and mPET showed that the influence of SVF on microclimate and PTC varied throughout the day. In the morning, the minimum SVF is effective for the eastern sidewalks, whereas in the evening, it is effective for the western sidewalks because the building adjacent to the sidewalk blocks solar radiation. In the afternoon, due to the angle of solar radiation being approximately 90 degrees from the ground, trees or other shading devices block solar radiation. Thus, minimum SVF is effective. These findings are associated with previous studies that show a significant correlation between SVF and thermal comfort index and reported that N– S orientation streets with buildings adjacent to sidewalks are beneficial to PTC (Acero et al., 2019; Achour-Younsi & Kharrat, 2016; Bourbia & Awbi, 2004; Ketterer & Matzarakis, 2014; Narimani et al., 2022; Pearlmutter et al., 2007).

The thermal walk observations in both seasons showed a significant difference in thermal sensation results with respect to microclimatic parameters. It was observed that people's thermal sensations vary spatially with the level of solar radiation and temporally with temperature and wind. The results are aligned with previous studies that show that people overestimate their thermal sensation under direct sunlight and wind speed (Azegami et al., 2023; Kotharkar et al., 2024; Lam & Hang, 2017; Lau et al., 2019; Peng et al., 2022; Sanusi et al., 2016). The presence or absence of wind can significantly impact how cold individuals feel, even at the same temperature. Wind increases the rate of heat loss from the body through convection, making the surroundings feel colder than the actual temperature (Lau et al., 2019; Yu et al., 2021).

The neutral mPET value for winter is 28°C, and that for summer is 32°C. This indicates the dynamic nature of human comfort preferences, showcasing the ability of individuals to adjust their thermal expectations following seasonal variations. The neutral mPET values for Nagpur are similar to a research conducted in in Kolkata, where the neutral PET was calculated and the resultant values were 27.5 °C for winter and 30 °C (summer) (Banerjee et al., 2020). The neutral mPET value also indicated that it is crucial to calibrate the thermal comfort index according to the local conditions to mark the actual thermal sensation through an objective assessment of the outdoor environment.

Conclusion

Walkability is a sustainable mode of transportation and an efficient last-mile connectivity option. In tropical countries, climate is an essential barrier to walkability. This paper presents a pilot study conducted on Nagpur's commercial street as a methodological approach for assessing pedestrian thermal comfort. This study shows the relationship between urban street geometry, microclimate, and pedestrian thermal comfort. This study highlights the importance of a multidimensional approach for understanding pedestrian thermal comfort's spatiotemporal dynamics. It emphasizes the need for a multi-duration study to identify issues concerning the time of day when pedestrians experience maximum thermal stress and the combination of urban geometry that affects pedestrian thermal comfort.

This study shows a strong correlation between urban geometry and pedestrian thermal comfort. For streets with a North– South orientation, the aspect ratio and sky view factor play essential roles, and their influence on pedestrian thermal comfort changes throughout the day. Maximum comfort is experienced on the eastern sidewalk in the morning and on the western sidewalk in the evening due to the shading effect. Both sidewalks have the same comfort level in the afternoon, except for places with direct shading. The ANOVA test outcomes highlight the important role of solar radiation in influencing thermal sensation votes (TSV), demonstrating the importance of shading strategies in mitigating discomfort. The determination of neutral mPET values indicates the need for area-specific calibration of thermal comfort indices at the local level, enabling the identification of critical areas that require specific interventions based on objective assessments.

This study advocates including objective and subjective parameters in comprehensively assessing pedestrian thermal comfort. This study explains the behavior of N–S oriented streets; thus, the results can be applied to N– S oriented streets in similar climatic conditions. Further study will be conducted using the same method for a large data sample in terms of the number of participants for the thermal walk and the streets of different orientations. This method can help urban planners and researchers identify critical areas for pedestrian thermal comfort and develop context-specific mitigative strategies

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