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Sidewalk Landscape Structure to enhance Pedestrian Thermal Comfort in Kathmandu Metropolitan City

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Abstract

The thermal comfort of pedestrians in the outdoor spaces of urban areas has deteriorated due to the urban densification. The street being a major outdoor space that can promote physical activity, and especially with the emerging concept of walkable cities, thermal comfort in streets should be given utmost importance. Thermal comfort for pedestrians is the absence of any sense of discomfort when interacting with the outdoor thermal environment. This paper aims to evaluate the effectiveness of various landscape measures (trees and pavements) to enhance pedestrian thermal comfort on sidewalks. The study has adopted the quantitative approach and used the simulation and questionnaire survey as methodological tools to meet its objectives. The study was conducted on both sidewalks of Durbarmarg, one of the dense and busy streets of Kathmandu. The microclimatic modeling software ENVI-met 5.03 lite was used for the simulation. The results of the simulation showed that increasing the leaf area density (LAD), tree canopy size and height can reduce the air temperature by 0.2°C and Mean radiant temperature by 4.86°C. Among the various pavement materials in various scenarios for the simulation, the light concrete pavement showed the highest decrease in terms of the air temperature (0.579°C) however the mean radiant temperature was highest (7.22°C) for the same material. Hence, high reflective surfaces reduce the surface /air temperature but it increases the mean radiant temperature and hence they might not be appropriate for the thermal comfort of pedestrians. The paving materials which showed a decrease in both air temperature and mean radiant temperature were porous concrete, flagstone, and brick pavers. The study concludes that proper selection of pavement materials and high leaf area density of trees can enhance the thermal comfort for pedestrians on the sidewalks of Kathmandu.

Keywords: *ENVI-met, Mean Radiant Temperature, Pedestrians, Thermal Sensation*

Introduction

Urban morphology is changing which has led to the phenomenon called Urban Heat Island Effect which elevates city temperatures, degrades urban comfort conditions, and increases cooling energy demand (Faragallah & Ragheb, 2022). In their study of the urban heat island in Kathmandu, Mishra et al. (2019) found an average temperature difference of 5 °C between forested and urban areas in the Kathmandu Valley. The authors also found an annual increase of 0 to 2 °C over the last 18 years. The outdoor environment has major essence in cities because it serves a variety of activities for pedestrians. The comfort level of outdoor spaces has a direct impact on the number of people present outside (Chen & Ng, 2012; Coccolo, et al., 2016; Hass-Klau, 1993; Hakim, et al., 1998). Under the umbrella concept of pedestrian comfort is pedestrian thermal comfort. The rough definition of thermal comfort for pedestrians is the pleasant feeling they have when interacting with the thermal environment surrounding them (Kasim, Shahidan, & Yusof, 2018). ASHRAE (1989) has defined human thermal comfort as a condition of mind that expresses satisfaction with the thermal environment, which is determined by various environmental and individual variables.

Outdoor thermal comfort is mainly related to thermo-physiology, i.e. physiology and heat balance of the human body (Hoppe, 2002) that is directly affected by meteorological conditions like wind velocity and direction, air temperature, and humidity. There are various parameters for outdoor thermal comfort. They can be categorized into subjective and objective. The subjective parameter consists of behavioral and psychological aspects whereas the objective parameter consists of air temperature, mean radiant temperature, metabolic heat, wind, humidity, and clothing insulation. Mean radiant temperature is an important parameter in assessing human comfort outdoors. While air temperature is a measure of cooling (or heating) by contact with air, mean radiant temperature is a measure of cooling (or heating) by exchange of radiant heat with all objects in the area (Sensible House, 2010).

Thermal comfort is particularly important in streets because they have a high potential to promote physical activity like walking and other outdoor activities (Kim, Lee, & Kim, 2018). Sidewalks run parallel to the streets and provide pedestrians mobility and access to buildings, parks, and so on. There are 3 zones on the sidewalks: the clear zone, the service zone, and the transition zone (Santos, Caccia, Samios, & Ferreira, 2019). Green spaces of properly designed landscapes are one of the most important bioclimatic design elements for outdoor thermal comfort (Georgi & Dimitriou, 2010). Trees provide direct shade by intercepting sunlight through their canopy (Sun et al., 2021). The different characteristics of vegetation like the foliage shape and dimensions, the height of the trunk, and leaf area density (LAD) have an impact on outdoor thermal comfort (Perini, Chokhachian, & Auer, 2018). LAD determines the airflow through the foliage (low or high). LAD affects plants' evapotranspiration, which results in reduced air temperatures and increased air humidity.

Paving materials also have a strong effect on the microclimate of the street and represent one of the major contributors to the urban heat island effect (Faragallah & Ragheb, 2022). Streets are traditionally constructed with an impermeable layer, it creates its microclimate due to the solar radiation reflected/absorbed by street surfaces, orientation, and geometry (Shishegar, 2013). The microclimate of streets affects the comfort of pedestrians walking. Walking is the most natural way of transportation in most of the cities including Kathmandu. Walking for short distances could be one of the promising strategies to reduce Vehicle miles traveled (VMT), transport-related energy consumption, and associated environmental impacts (Ewing, et al., 2020). Walkability has been cited by many urban planners as the factor that makes a city sustainable. One of the ways to promote walkability is to improve outdoor thermal comfort for pedestrians.

The current urbanization and motorization in Kathmandu do not provide a safe and pleasant environment for walking. Most streets do not even have sidewalks, and those that do exist are either poorly maintained or occupied by parked vehicles and street vendors (Regmi, 2019). Many street improvement projects carried out under the Municipal Infrastructure Improvement Project (MIIP), Kathmandu Sustainable Urban Transport Project (KSUTP) have focused on vehicular movement and drivers' convenience rather than pedestrian comfort, convenience, and safety (Shrestha, 2011). Sidewalks were widened and built considering the durability of paving materials, but without considering the thermal impact on the microclimate of the street. Most of the trees along the streets are planted indiscriminately and only for beautification, without considering their impact on the microclimate of the street. No significant studies have been done to improve the thermal environment of the sidewalks of Kathmandu. Therefore, the study aims to investigate the existing structure of the sidewalk landscape (mainly trees and pavements) considering the microclimate of the selected street section in Kathmandu and to propose the necessary landscape interventions (trees and pavements) that will improve the thermal environment and the thermal comfort of the pedestrians.

Materials and Methods

Study Area

The selected case study area, Durbarmarg (informally known as Kings' Way), is located in the metropolis of Kathmandu (27.712611N, 85.317972E). and is a very dense and lively street in Kathmandu. It leads to the royal palace of Narayanhiti. Durbar Marg was built in 1961 by the then Crown Prince Birendra Bir Bikram Shah Dev.

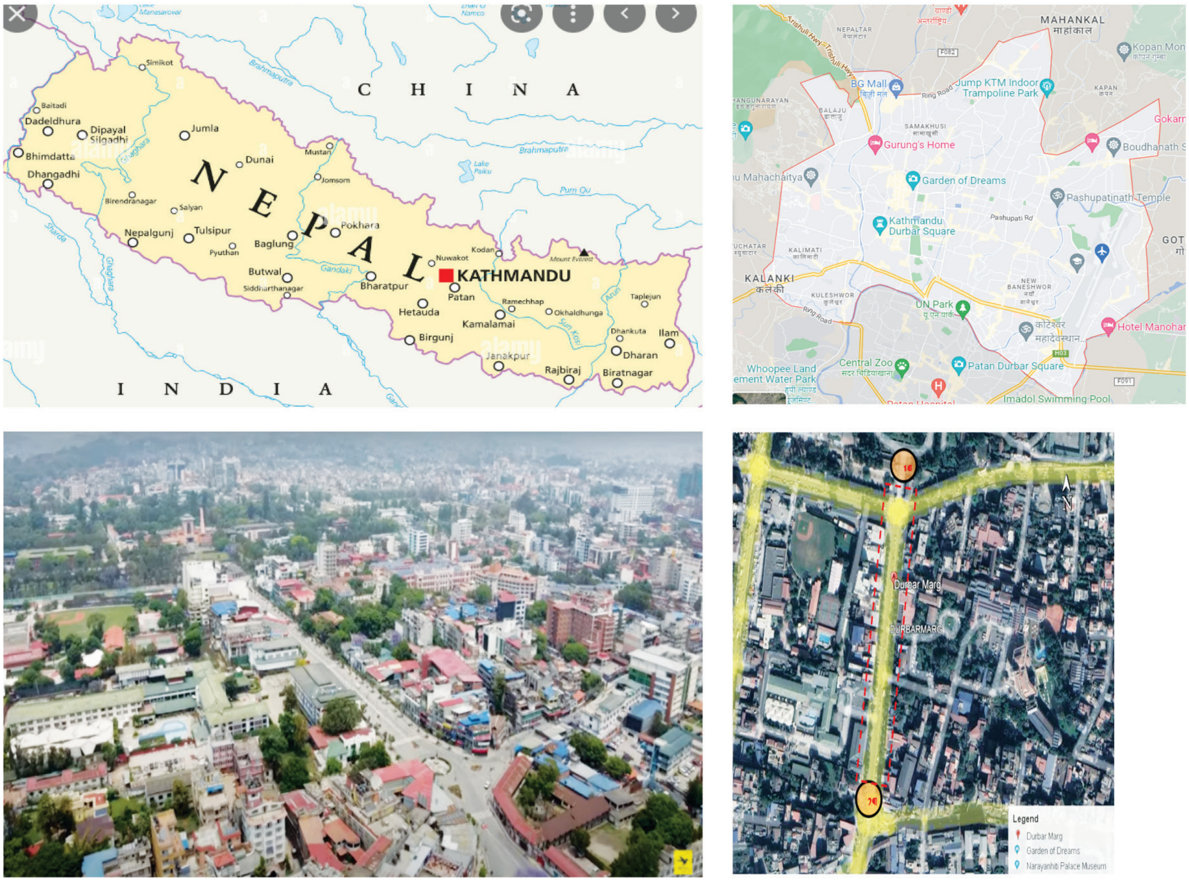

Figure 1: Site map Source: Google maps and Saurav Agrawal (Kathmandu Kingsway-A Drone film 4K) for the bird view picture (bottom left)

Figure 2 shows the blow-up plan of Durbarmarg: the selected street section. The stretch is about 300 m long. The pedestrian flows on the street are immense. For simplicity, the sidewalks are referred to as east-facing sidewalk and west-facing sidewalk. The east-facing sidewalk has street furniture while the west-facing sidewalk has no street furniture.

The number of pedestrians passing the street at a certain point was recorded at different times of the day and on both sidewalks. It was found that pedestrian flow was greater on east-facing Sidewalk than west facing sidewalk. On June 27 at 4:30 p.m., approximately 36 people passed in one minute. The width of the sidewalks, trees height and canopy

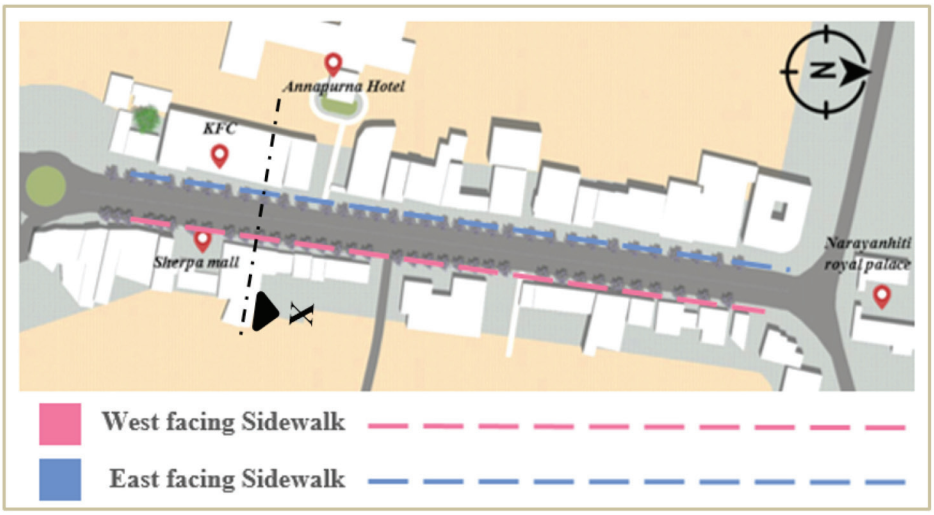

Figure 2: Blow up plan of the Selected Street Section: Durbarmarg

size were also measured. The planted street tree is Jacaranda Mimosifolia and the width of the sidewalks varies within the building frontage and the different sections of the sidewalks. Most of the pavement material is concrete.

The microclimate of the selected street section was also studied. The climatic parameters air temperature, relative humidity was measured with KOBO RH/T data logger (MX2302 and MX2304) for 12 days starting from June 29, 2022 to July 10, 2022 on both sides of sidewalks. The device was calibrated with device on DHM (Department of Hydrology and Meteorology) (See Appendix B) and it was placed on site as shown in the figure 3.

Questionnaire Survey

The thermal comfort survey was done to gain a perception of the thermal environment on both sidewalks of the selected street section for almost 7 days in favorable climatic conditions. A random sample of 36 pedestrians was taken for the survey. The number of people surveyed on east-facing sidewalk and west-facing sidewalk were 21(58%) and 15 (42%) respectively. The main target for this survey were pedestrians however people who spent their most time outdoors in the street like the vendors and guards were also surveyed. The respondents were 83% pedestrians, 11% security guards and 6% vendors.

The questionnaire was divided into 5 parts where first part was to be filled by the surveyor by observation. The rest of the parts consisted of demogrpahic details, purpose of visit, thermal sensation and preference for microclimate (See Appendix A). Kobo Toolbox was used for the analysis of the survey data.

Simulation with ENVI-met software

ENVI-met 5.03 was used to simulate the outdoor comfort of the sidewalks. Envi-met was chosen for the simulation because it has several advantages. The modeling system simulates the dynamics of microclimate within a daily cycle. Different vegetation forms can be generated in the model. ENVI-met considers the physiological processes of evapotranspiration and photosynthesis rather

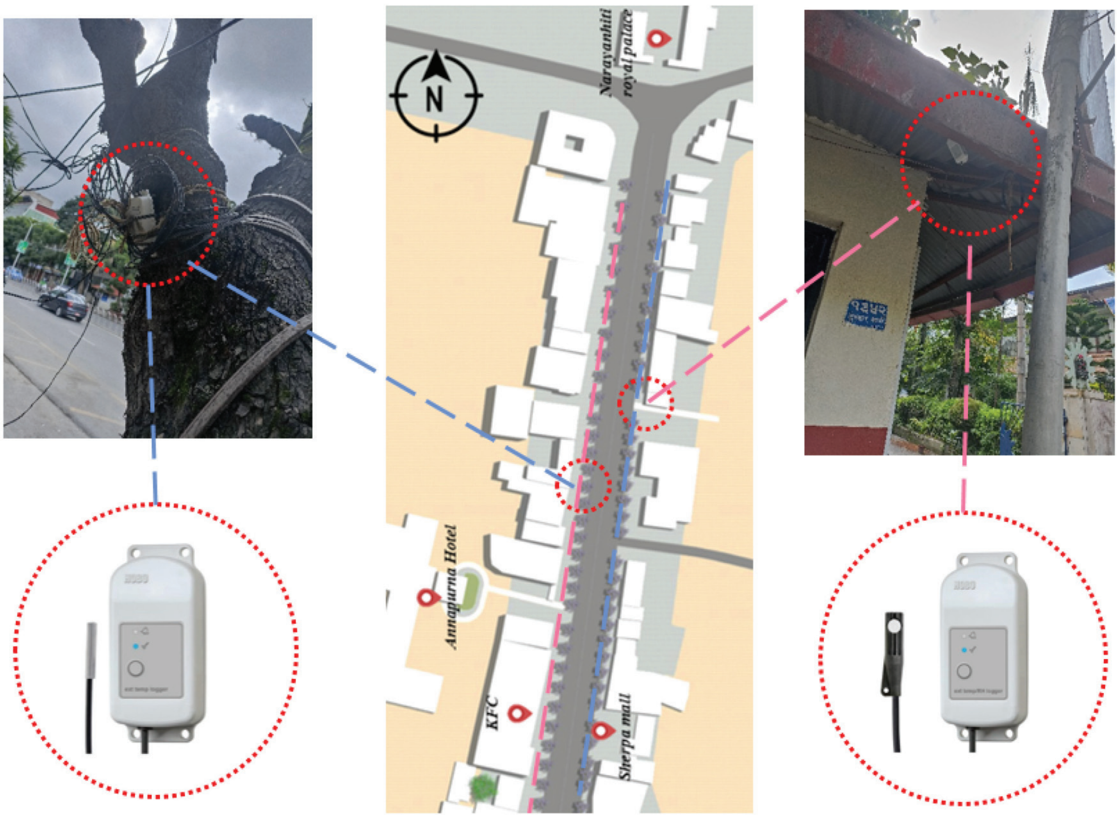

Figure 3: Placement of Hobo data loggers on East facing Sidewalk (left) and West facing Sidewalk (right) respectively.

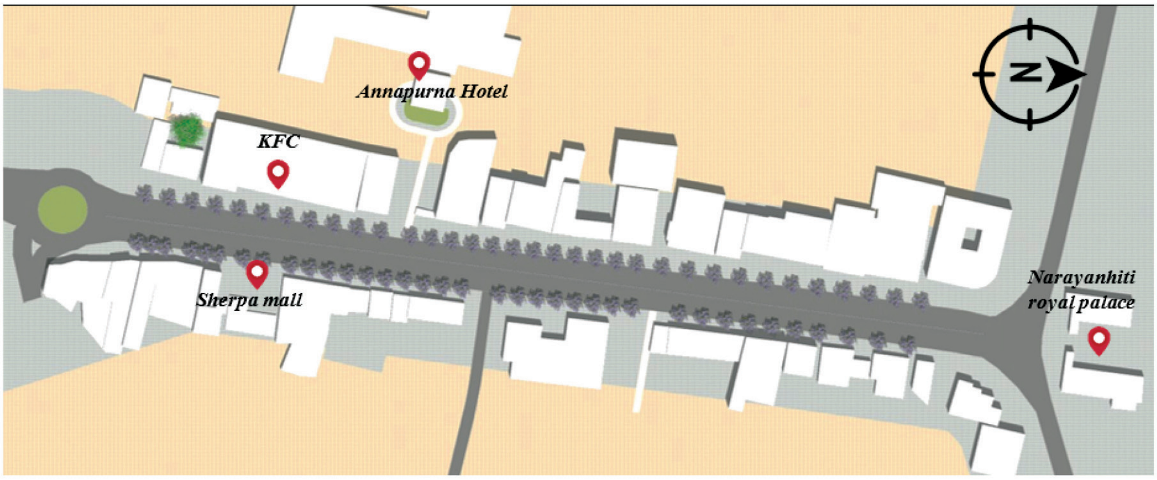

Figure 4: Part of the street section taken for simulation

than vegetation as a porous barrier to wind and solar radiation. A limited number of inputs are required to run the model with a large number of outputs. ENVI-met can calculate Tmrt (mean radiant temperature), the most important parameter in thermal comfort calculations.

A stretch of 150m (See fig.5) was selected for the simulation since the lite/free version of software has limited domain size of 50 X50 X30. The model size in domain is 38 X 50 X 15 with dx 3 m dy 3m and dy 3m. The north is tilted 8 degree towards left with the grid north. The model location is set as 27.712611N, 85.317972E.

Simulation day meteorological Conditions

The simulation day was chosen as 7/7/2022 (one of the hottest day during the 12 days of measurement). The simulation was done for 12 hours starting

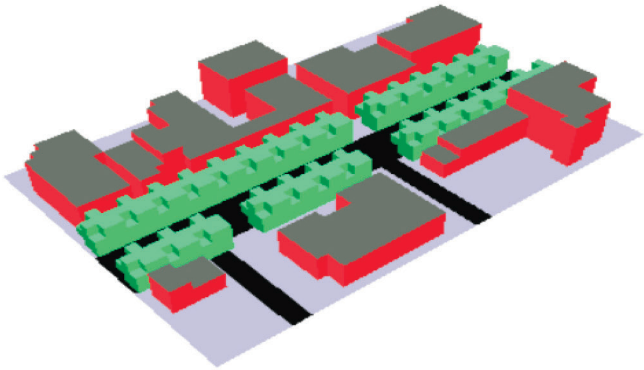
Figure 5: 3D model of Base Case Scenario

from 7 am in the morning for the same day. For the simulation, simple forcing of the data has been done using hourly temperature and relative humidity data. The maximum temperature for the day was 33°C and minimum was 22.14°C at 1 pm and 3 am respectively. The input data for the simulation are shown in figure 7 and Table 1.

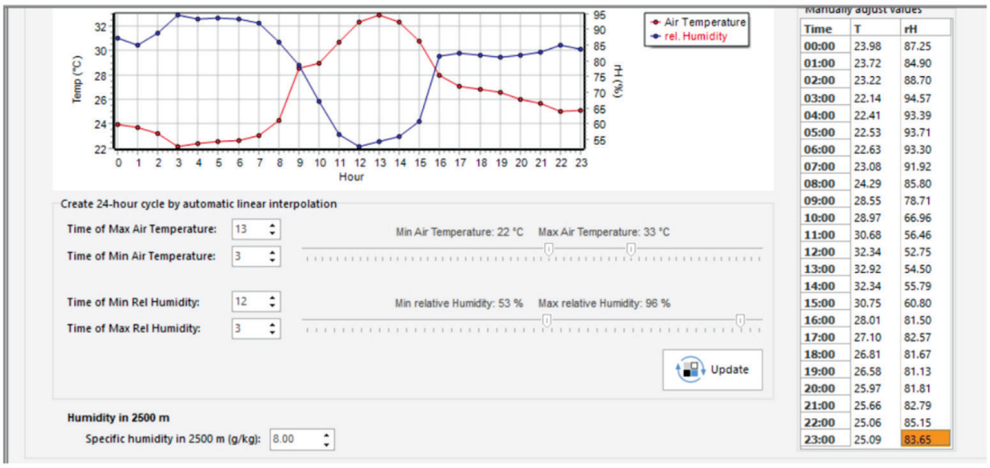

Figure 6: Meteorological conditions for simple forcing

Table 1: Input data in Envi-met for simple forcing

Time of max temp	Time of min. temperature	Time of max Relative Humidity	Time of min Relative humidity	Wind Speed	Wind direction
13:00	3:00	3:00	12:00	2.34 m/s	270

The wind speed data for the particular day was taken from department of hydrology and Meteorology as there was no device available to measure the wind at the selected site. The average wind speed for the day was 2.34 m/s.

Validation of ENVI-met results

For the validation of the ENVI-met results, the hourly temperature and relative humidity from the time 8 am to 7 pm was compared with the results obtained for the base case scenario from the ENVI-met 5.03 results as shown in the figure 8.

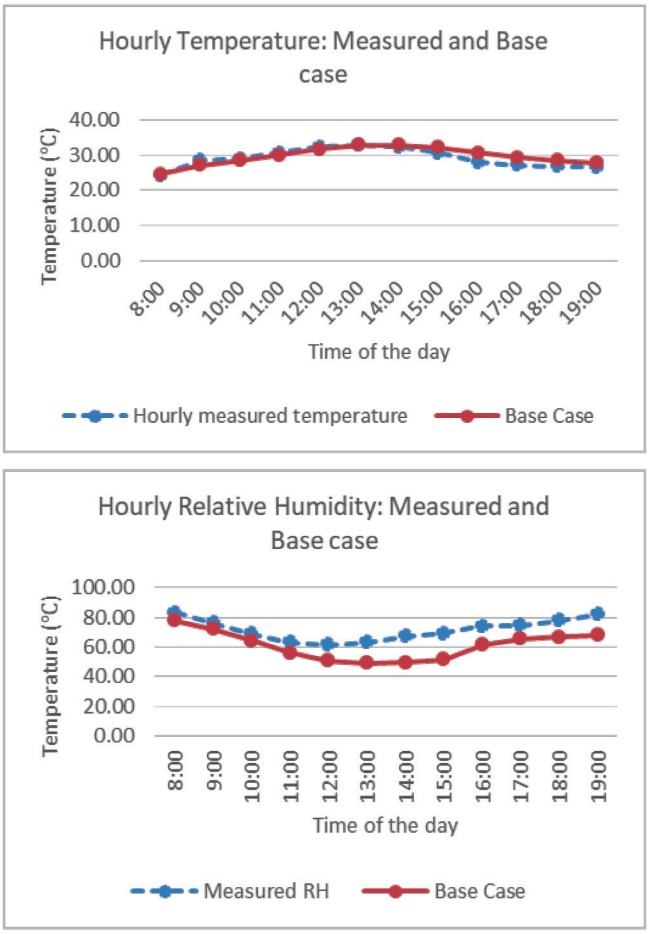

Figure 7: Hourly temperature and relative humidity measured from the device and base case scenario

The average temperature difference between the hourly temperatures: measured and base case throughout the day is 0.55! and the average relative humidity difference between the hourly relative humidity: measured and base case throughout the day is 10%. The discrepancy could be because vegetation other than street trees was not considered in the simulation, the devices were placed on the sidewalks, and the difference in microclimate could also play a role, since the climate data were obtained from the nearest station (Lazimpat), while the devices were placed exactly on site.

Results and Discussion

Thermal comfort varies with time of day. The authors assumed that there was some relationship between time of visit and thermal comfort in summer. However, 19 (54.28%) of the respondents visited the street between 10 am and 2 pm, the time when temperatures are highest. Since most of the respondents visited this street for work reasons, it seems that a visit during the day is reasonable.

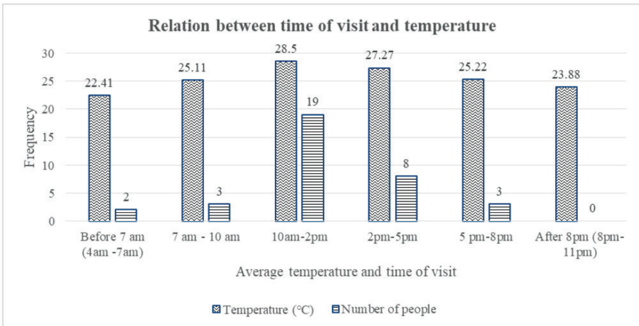

Figure 8: Relation between time of visit and temperature

36% of respondents preferred both sidewalks, while 39% of respondents preferred an east-facing sidewalk, with the remaining 25% preferring a west-facing sidewalk. Also, as mentioned earlier, there were more people on the east-facing sidewalk than on the west-facing sidewalk. Since there was no significant difference in air temperature on the east and west facing sidewalks, as shown in the figure 10, the greater number of people on the east facing sidewalk could be due to the presence of street furniture and the number of restaurants on the east facing sidewalk. Overall, the east-facing sidewalk appeared to be more lively than the west-facing sidewalk.

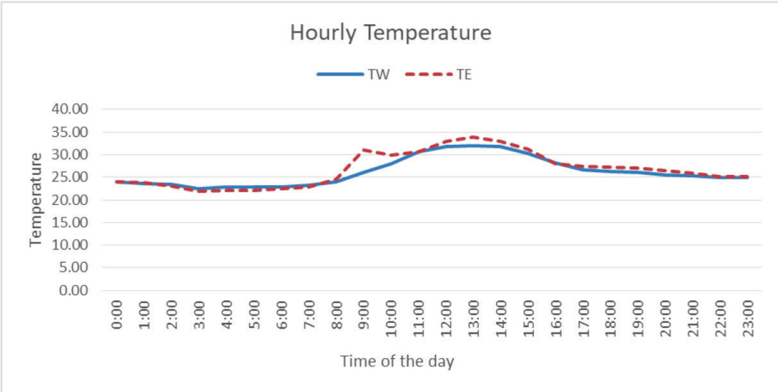

Figure 9: Hourly temperature of east-facing and west-facing Sidewalks.

The activity mapping was also done during the survey. The figure 11 shows the different location of survey within the selected street section with the pedestrians involved in various activities.

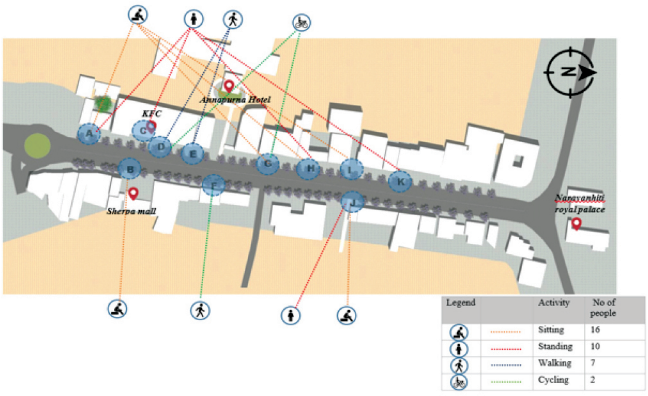

Figure 10: Location of the survey within the site with the pedestrians involved in various activities

Thermal comfort is different in different parts of the street because the microclimate is different in different parts of the street. As shown in figure 12, 41.67% of respondents chose a particular place to sit/stand/walk because it is covered with trees, and 25% of respondents chose a place because the building provides shade. Thus, the physical characteristics of the street play an important role in improving thermal comfort.

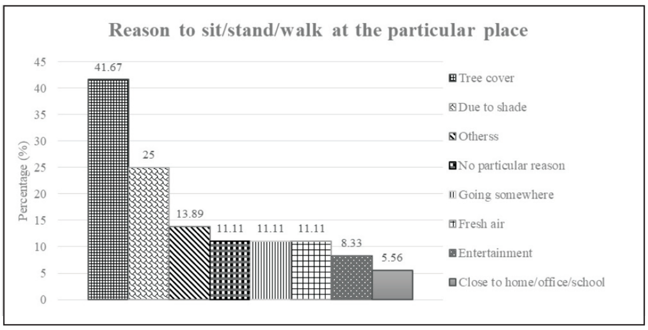

Figure 11: Reason to sit/stand/walk at the particular place

Sidewalk pavement also have a strong influence on the street microclimate and are one of the main contributors to the urban heat island effect (Faragallah & Ragheb, 2022). The paver materials vary within the building frontage and the different sections of the sidewalks. However, the majority of the sidewalks are made of concrete. Respondents were asked whether or not they felt the heat on the sidewalk. The majority of respondents (approximately 63.89%) felt the heat from the sidewalk, as shown in Figure 13.

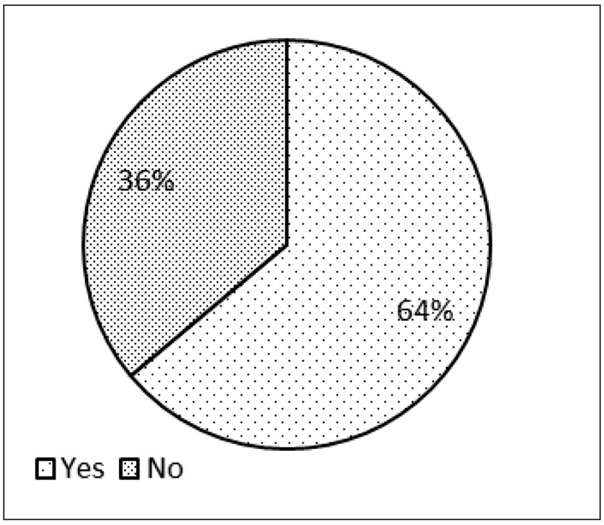

Figure 12: Heat from the pavement

Respondents were asked about their thermal sensation, skin condition, and preference for microclimate at the time of the survey. 13 (36.11%) out of 36 respondents felt hot, 2 (5.56%) felt very hot, 10 (27.78%) felt warm, while the rest of the respondents had a neutral thermal sensation. The thermal sensation votes are shown in Figure 14. 38.89% of the respondents had sweaty skin during the survey

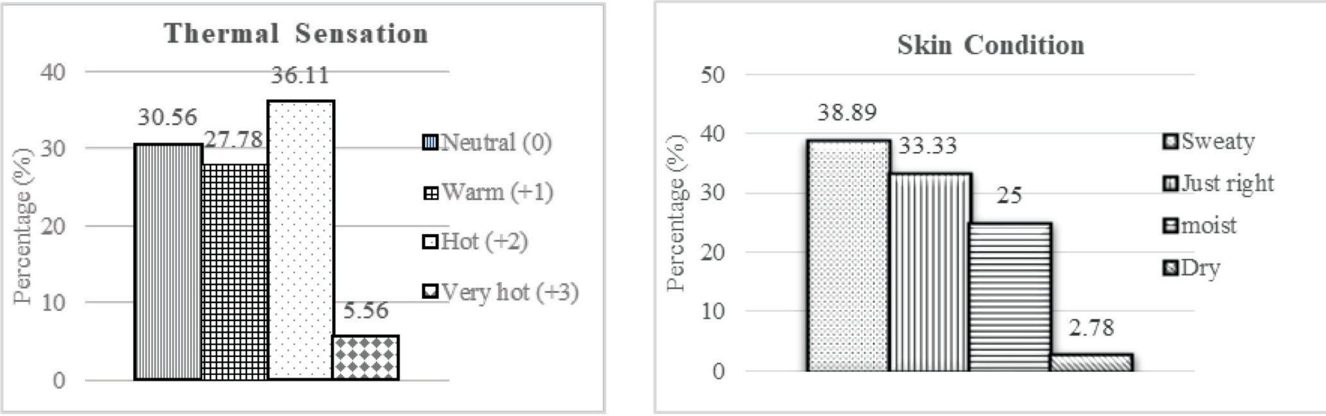

Figure 13: Thermal Sensation Votes and Skin Condition

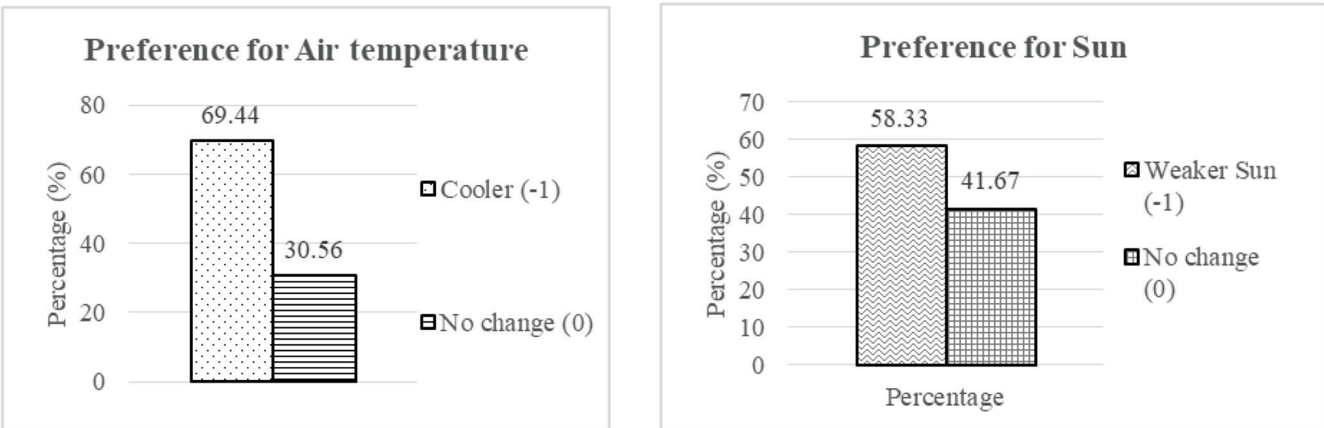

Figure 14: Preference for air temperature and Sun

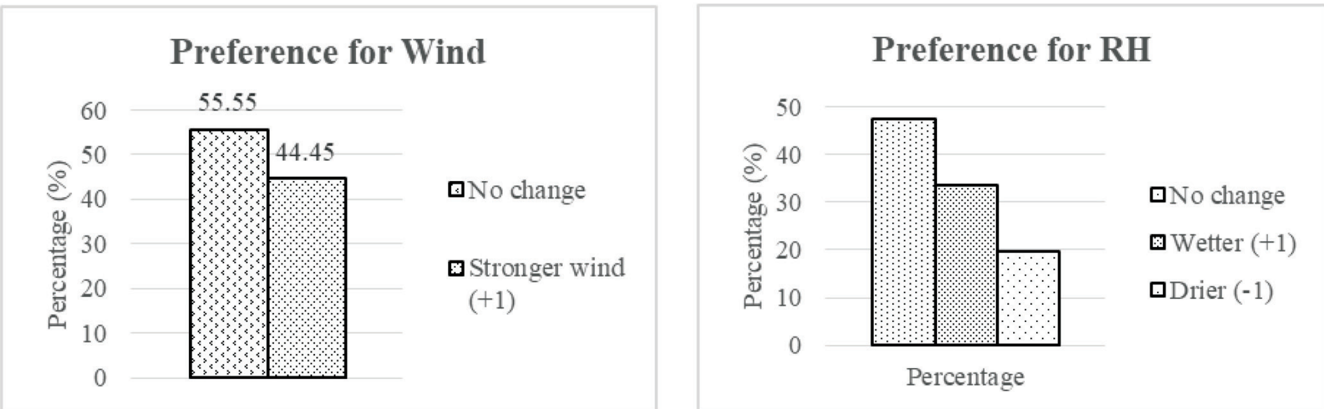

Figure 15: Preference for wind and Relative Humidity

In addition to that, 69.44% of people preferred cooler air temperature, the rest was satisfied with the air temperature. Similarly, 58.33% preferred weaker sunlight for thermal comfort. The majority of respondents preferred stronger wind (55.55%), and for relative humidity, 47.22% preferred no change in Relative Humidity. Since the majority of respondents had either a hot or warm thermal sensation and preferred a change in microclimate, it can be concluded that the thermal environment of the selected street section is not comfortable for pedestrians.

Simulation results

Different scenarios were created by changing the parameters like the orientation, no. of planting strips, spacing between trees, leaf area density and the pavement materials. The summary of scenarios is presented in the table 2.

Table 2: Summary of Different Scenarios for Simulation

S.N	Scenarios	Trees	Pavement
1	BC: Base Case Scenario	Low LAD trees (9m X 10m)	Concrete pavement dirty/used
2.	O1: Orientation changed to EW	Same as base case	Same as base case
3.	V1: Low Leaf Area Density trees(LAD) changed to High LAD	High LAD trees (9m X 10m)	Same as base case
5.	V2: Trees Canopy (13m) and height (15m) changed.	High LAD trees (13m X 15m)	Same as base case
6.	V3: Median with trees introduced in between road (3m X5m)	High LAD trees (9m X 10m)	Same as base case
7	P1: Pavement material same as BC	No trees	Same as base case
8	P2:Pavement material changed	No trees	Light coloured concrete
9	P3:Pavement material changed	No trees	Dark coloured Concrete
10	P4: Pavement material changed	No trees	Interlocking concrete blocks
11	P5: Pavement material changed	No trees	Porous concrete
12	P6: Pavement material changed	No trees	Red brick
13	P7: Pavement material changed	No trees	Flagstone
14	P8: Pavement material changed	No trees	Limestone
15	P9: Pavement material changed	No trees	Coloured Asphalt in road.
16	V1P1: Pavement and vegetation parameter changed.	High LAD trees (9m X 10m)	Pavement same as base case
17	V1P2: Pavement and vegetation parameter changed.	High LAD trees (9m X 10m)	Light color Concrete
18.	V1P5: Pavement and vegetation parameter changed.	High LAD trees (9m X 10m)	Porous Concrete
19.	V1P7: Pavement and vegetation parameter changed.	High LAD trees (9m X 10m)	Flagstone

Comparison of Simulation Scenarios

Different scenarios created so far have been compared in terms of potential air temperature and mean radiant temperature. The figure 17 shows the air temperature and mean radiant temperature difference among the various scenarios considering the orientation and vegetation parameters. When the orientation was changed to EW orientation, potential air temperature increased by average of 0.44°C and mean radiant temperature increased by average of 6°C. It is due to the fact that the EW oriented sidewalks are likely to get long exposure solar radiation than NS oriented sidewalks. The potential air temperature decreased by average 0.074°C when the low LAD trees were changed to high LAD trees (Scenario 1: Base Case to Scenario V1). The potential air temperature decreased by average of 0.197°C when the tree canopy size was increased to 13 m and height was increased to 15m (Base Case to V2). The mean radiant temperature decreased by almost 4.86! in the same case. Similarly, when the trees (3m X5m) were introduced in the median, there was no significant change in the air temperature, however the mean radiant temperature decreased by 3.41°C.

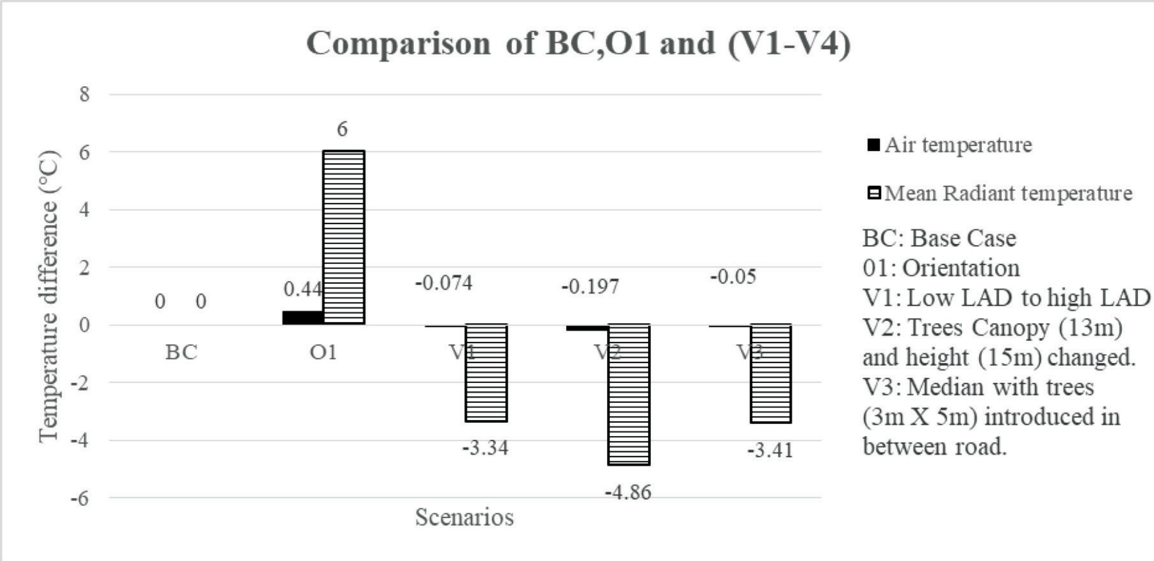

Figure 16: Comparison of Scenarios: BC, O1 (Changing orientation) and (V1-V4)

The figure 18 shows the air temperature and mean radiant temperature difference by changing the pavement materials. Among the various pavement materials in various scenarios for the simulation, the light concrete pavement showed the highest decrease in terms of the air temperature (0.579°C) however the mean radiant temperature was highest (7.22°C) for the same material. This is due to the fact that it has more albedo and hence than reflects more solar radiation than the other pavement materials used in the simulation. The reflected solar radiation is then absorbed by the pedestrians.

Hence the material which decreases the air temperature might also not improve or worsen the thermal comfort for the pedestrians. The materials which showed the decrease in both air temperature and mean radiant temperature were porous concrete, flagstone and brick pavers.

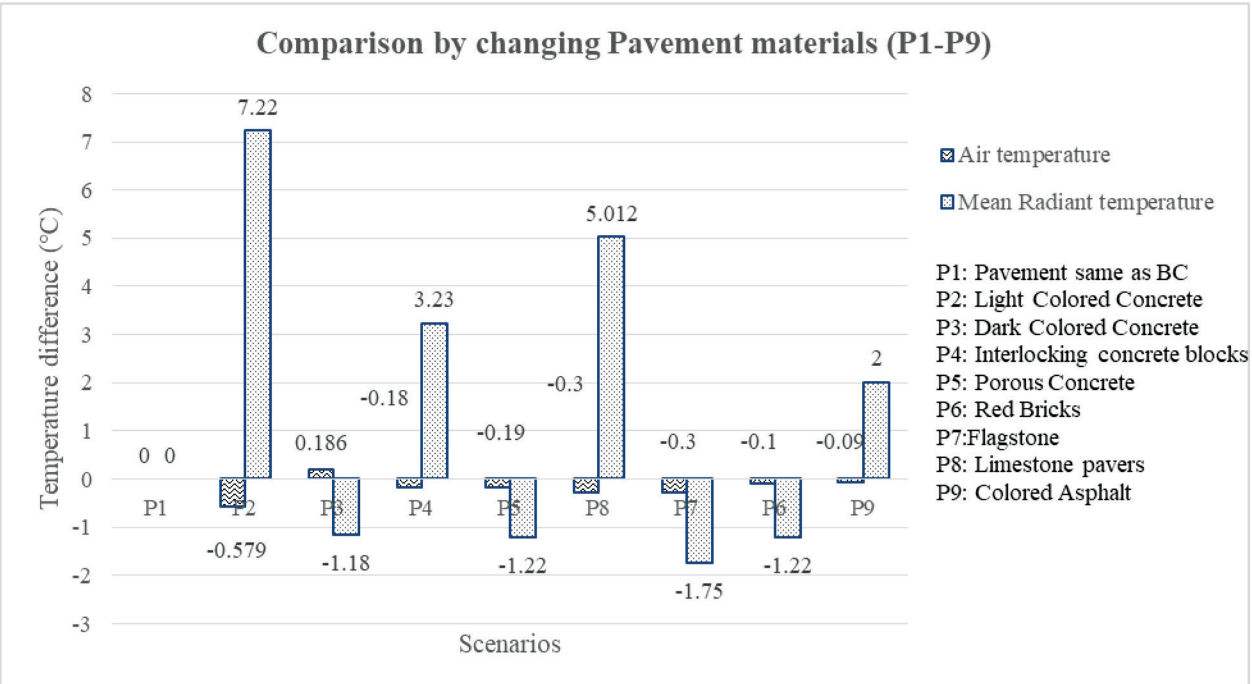

Figure 17: Comparison of Scenarios by changing Pavement materials (P1-P9)

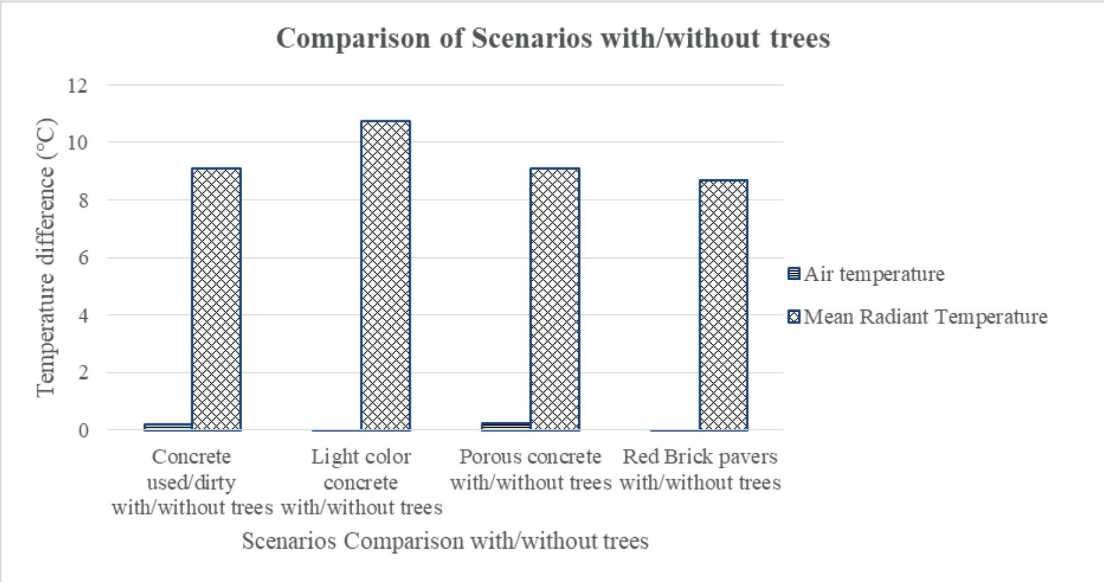

Figure 18: Comparison of Scenarios V1P1, V1P2 (High LAD trees with pavement light color concrete), V1P5 (High LAD trees with pavement porous concrete), V1P6 (High LAD trees with pavement red bricks).

When comparing the scenarios with and without trees (V1P1 and P1, V1P2 and P2, V1P5 and P5, V1P6 and P6), as shown in Figure 45, the potential air temperature difference was found to be highest for porous concrete (0.22°C) and the mean radiant temperature difference for light-colored concrete. Also, the potential air temperature difference with and without trees ranges from 0.045°C to 0.22°C, and the mean radiant temperature difference with and without trees ranges from 8.65°C to 10.71°C. Therefore, the presence of trees on the street has a great influence on the thermal environment and thermal comfort of pedestrians.

Conclusion

The study concludes that the physical characteristics of the sidewalks such as the shade of buildings, the presence of vegetation (trees), orientation and the paver materials affect the thermal environment of the sidewalks. Pedestrians are more prone to thermal stress on EW sidewalks than NW-oriented sidewalks, which is also consistent with the results of other studies (Lin, Cho, & Hsieh, 2021). Among the various vegetation parameters considered, leaf area density is of utmost importance to maintain the thermal comfort. Among the various pavement materials considered, the pervious concrete, brick pavers enhances the thermal comfort for pedestrians. For the high reflective surfaces, the surface /air temperature is reduced but it increases the mean radiant temperature and hence might not be appropriate for the thermal comfort of the pedestrians. This also comply with the findings of other studies **(**Taleghani & Berardi, 2017; Li, et al., 2012). It can be concluded that certain interventions in sidewalk landscape (trees and pavements) can make significant difference in the microclimate of the street. Hence, the street design guidelines in Kathmandu should also consider the thermal environment of the street/sidewalks while considering the landscape design of the street. Brick pavers, flagstone and porous concrete (evaporative cooling effect) can be used instead of traditional impervious concrete. Trees with high leaf area density can be used to provide the cooling effect in hot climate. Similar studies can be done to enhance pedestrian thermal comfort in Terai region of Nepal. These kind of study /research should be done and will be useful in also creating the public pocket parks within the city to get the maximum thermal benefit.

The results of questionnaire survey show that the sidewalks were not comfortable in terms of thermal comfort. However, the sample size of the survey should be increased to get more accuracy. Further research is needed as the study was conducted in a typical street section and only during the few summer days. In temperate climatic regions like

Kathmandu, the study is also important in winter. However, in this study, the thermal comfort of pedestrians was investigated and evaluated only in summer. Various parameters like the street aspect ratio, tree species and other landscape feature like water bodies can be considered for the further studies.

Acknowledgement

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Appendix A

S.N	Date-Time	Parameters	Hobo MX 2304	DHM	Diff .RH	Diff. Temp.
1	06/23/2022 15:15:00	T (°C)	28.87	28.72		0.15
		RH(%)		38.46	3.54	
2	06/23/2022 15:20:00	T	28.87	28.84		0.03
		RH		38.07	3.93	
3	06/23/2022 15:25:00	T	29.00	28.93		0.07
		RH		37.72	3.28	
4	06/23/2022 15:30:00	T	29.13	28.99		0.14
		RH		37.26	3.74	
5	06/23/2022 15:35:00	T	29.13	29.13		0.00
		RH		37.05	2.95	
6	06/23/2022 15:40:00	T	29.30	29.19		0.11
		RH		36.94	3.06	
7	06/23/2022 15:45:00	T	29.34	29.06		0.28
		RH		37.28	2.72	
8	06/23/2022 15:50:00	T	29.21	28.87		0.34
		RH		37.4	1.6	
9	06/23/2022 15:55:00	T	29.08	28.87		0.21
		RH		37.7	2.3	
10	06/23/2022 16:00:00	T	29.17	28.97		0.20
		RH		37.08	1.92	
11	06/23/2022 16:05:00	T	29.34	29.08		0.26
		RH		36.58	2.42	
12	06/23/2022 16:10:00	T	29.56	28.99		0.57
		RH		36.95	1.05	
	Average difference				**2.71**	**0.20**