

Modelling the Impact of Various Strategies for Improving the Outdoor Thermal Comfort at a City Level



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Abstract One of the greatest environmental concerns for the long-term viability is to develop sustainability of future cities and to plan heat mitigation techniques for improving human outdoor thermal comfort. In this research work, a case study for Ahmedabad City has been considered which has hot, semi-arid climate-Bsh based on Köppen climate classification and aim of the study is to improve the outdoor thermal comfort and to plan heat mitigation strategies of Ahmedabad City, Gujarat, India, by assessing the outdoor thermal comfort of a city with analysing mean radiant temperature with thermal indices such as PET, PMV/PPD and UTCI with the application of ENVI-met V5.0.2 Software. For conducting the study, an urban canopy of Ahmedabad City has been examined from Maninagar area, and it has an administrative boundary of 7692.33 m² was model in ENVI-met (SPACES). The analysis was done during 09 May 2021 a hot summer day and 17 December 2021 a cool winter day to create a challenging environmental situation, and the input data for the simulations process are based on the meteorological station of GPCB located in Maninagar area. Software simulations were performed (for 24 h), and based on simulation of modelling, the four different case scenarios in ENVI-met model result are presented. The simulated results show that the suggested strategies have an effect on OTC, which means adopting case-2 and case-3 in particular location can reduce the temperature around 1.5–2 °C with Tmrt reduce up to 1.02–6.20 °C in summer and also, adopting case-2 and case-3 in particular location can increase the temperature around 0.5–1.0 °C in winter. The study provides better understanding of heat mitigation strategies on human thermal comfort at a city level (Ahmedabad), and the findings of this research provide finer suggestions for improving outdoor thermal comfort environment.

Keywords Envi_met software · Human thermal comfort · Urban microclimate · Residential area · Ahmedabad City India

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Abbreviations

| | |
|------------------|---|
| ASHRAE | American Society of Heating, Refrigerating & AC for Engineers |
| CPCB | Central pollution control board |
| EN 16798-1 | Basics of Thermal Comfort |
| GPCB | Gujarat pollution control board |
| ISO 7730 | Ergonomics of the thermal environment |
| OTC | Outdoor thermal comfort |
| PET | Physiological equivalent temperature |
| PMV | Predicted mean vote |
| PPD | Predicted percentage of dissatisfied |
| RH | Relative humidity |
| SVF | Sky view factor |
| T _a | Air temperature |
| T _{mrt} | Mean radiant temperature |
| UHI | Urban heat Island |
| UTCI | Universal thermal climatic index |

1 Introduction

The world is seeing rapid urbanization, as well as global warming and climate change. As a result, the role of urban planning, design and architectural production plays a crucial role to accomplish outdoor thermal comfort. As a result, one of the primary variables that must be addressed in order to achieve outdoor thermal comfort and construct cities that are environmentally friendly and are capable of achieving the highest degree of outdoor thermal comfort is the urban climate. A large number of publications on urban climate have been produced in order to deal with the climate of the city, which can play a significant role in enhancing urban climatology for better designing and mitigating the effects of climate change on the city's rapidly growing population. As a result, sustainable city planning is a step forward in reducing cities harmful effects on the environment.

1.1 Effect of Climate Change

In weather forecasting, climate change may contribute to heat warnings and medical issues. Many studies have been conducted in recent decades to improve the outdoor thermal comfort, and it has been demonstrated that a comfortable outdoor thermal environment can promote outdoor activity, improve urban climatology, and improve human physical and mental health. The thermal budget of the human body is highly

influenced by the sun's radiation, convection in the surrounding air and sweat evaporation which will cause several of health problems for humans. As a result, extended heat exposure can lead to a range of health problems, including heat rashes, heat cramps and heat exhaustion to potentially fatal heat strokes (Abdollahzadeh et al. 2021; Gajjar 2019).

Definition of Thermal Budget—The skin must be around 33 °C to sustain a consistent flow of heat from the human body's core (37 °C) to the surrounding environment.

1.2 What is Thermal Comfort

The ASHRAE 55 standard thermal comfort is defined as “the mental condition in which a particular situation or a person's satisfaction is expressed with the thermal environment.” It is a subjective opinion varies from individual perception based on the age group, standard of livings, body type, metabolism and the type of clothes worn during every season and also depends on various climatic factors. More than 165 thermal comfort indices have been established to evaluate the thermal environment by taking external factors and the human body's energy balance into account for both indoor as well outdoor thermal environment (Atwa et al. 2020; Kumar et al. 2020).

To proceed with the research study, the paper is divided into five sections. As discussed earlier, the part 1 will be the introduction part of the research study then, the second part will be the methodology with study area which will provide the geographic and climatic context as well as the studied solution methods and model validation, while Sect. 3 contains the results and discussion and lastly, and Sect. 4 contains the conclusions.

The research aims to focus on improving the outdoor thermal comfort and to plan heat mitigation strategies of an Ahmedabad City, Gujarat, India, by assessing the outdoor thermal comfort of a city with analysing mean radiant temperature with thermal indices such as predicted mean vote/predicted percentage of dissatisfied, physiological equivalent temperature and universal thermal climatic index with the application of ENVI-met software and also to investigate the levels of human thermal comfort.

2 Methodology

This section will firstly give the basic information regarding the case study and geographic condition with climate context of the research area. The key focus of this case study is Chaturbhuj colony Kankaria, located in Maninagar area in Ahmedabad City, Gujarat, India, and it is characterized by a hot semi-arid climate. Secondly, it describes a numerical simulation software that can be used to assess the microclimate in outdoor areas. The software considers all environmental characteristics including

the mean radiant temperature, the air temperature, the relative humidity and the wind speed (Barakat et al. 2017; Bruse 1998).

2.1 Case Study: Chaturbhuj Colony, Maninagar, Ahmedabad

The study area which was selected to conduct the research work is a small urban pocket from Maninagar area of Ahmedabad City has been considered which is located at coordinates of latitude 23° 0' 4" and Longitude 72° 35' 45", and it has an administrative boundary of 7692.33 m² to form a better perspective in hot semi-arid climate to assess how different strategies may improve outdoor thermal comfort conditions. Based on simulation of modelling, the four different case scenarios in ENVI-met (SPACES) with the grid size of (44*45*38) (X*Y*Z Grids) as our case study with base case scenario and other three case were model for simulation and evaluated, and then, the plan is to evaluate the area for thermal performance and to plan the various heat mitigation strategies to improve outdoor thermal comfort (Figs. 1 and 2).

Summer, monsoon and winter are the three primary seasons in Ahmedabad. The temperature is high from March to June, where it feels like heatwave with average summer day light savings time of 6:00 AM to 19:15 maximums with high temperature of 35–46 °C and average minimums of 40.5 °C. From mid-June to September, the south-west monsoon offers a humid environment with annual average rainfall of roughly 800 mm, while winter lasts from November to February, with December and January being the coldest months. It has a 3 m/s average wind speed and an 8 m/s maximum wind speed.

2.2 Software Selection for Conducting the Study

The main concern of the study is to selecting best software available to achieve the purpose of the study. Because field measurement takes time and requires a lot of manpower, equipment and expense. It is hard to conduct on field measurement and get the accurate meteorological data. There are various softwares available for evaluating outdoor thermal comfort. To proceed with the study, ENVI-met software was selected based on the literature review and most widely used software to conduct the research on urban microclimate. ENVI-met (Bruse 1998) is a gridded 3D model, and it is a numerical model that simulates of meteorological variables in a gridded domain. It uses a holistic approach in which all the different aspects of a microclimate are linked and simulated together in one model.

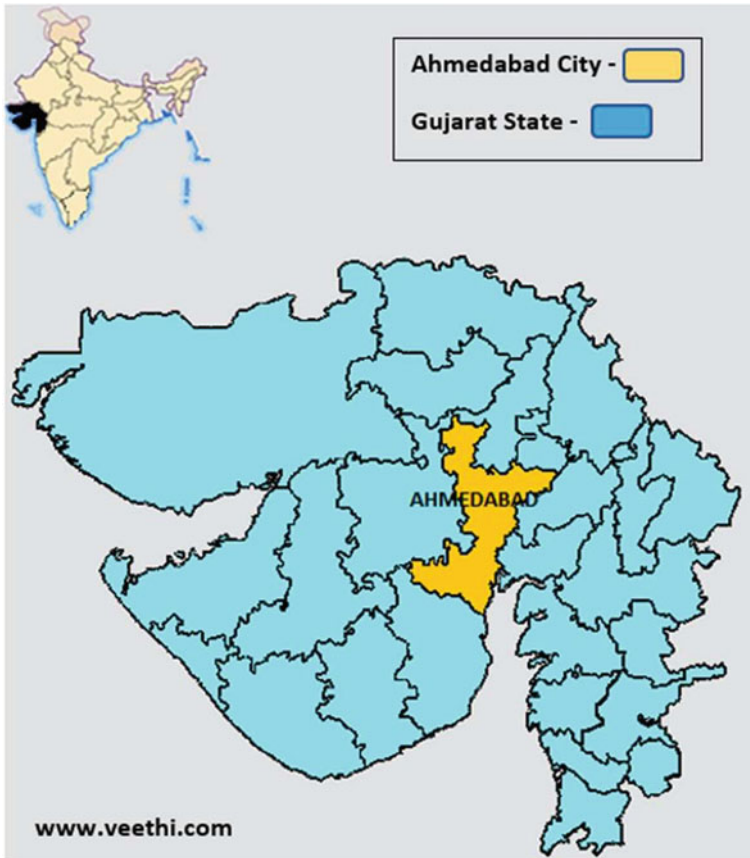


Fig. 1 Map of Gujarat showing Ahmedabad City

2.3 Methods

To conduct the study and to perform simulation for better thermal performance, a meteorological data of Maninagar weather station has been collected for performing simulations. The station which records meteorological data is located in Maninagar area itself at a coordinate of 23.02°N , 72.58°E which has been used for simulation in ENVI-met software. The weather data has been downloaded from CPCB Website (historical data) and used for the best result of simulation.

The software simulation was performed for extreme condition to evaluate the outdoor thermal comfort for the hottest day in summer as well coldest day in winter, and selected day for the hottest day was (09-05-2021), where temperature reaches maximum up to 44°C at 15:00 in afternoon, and the coldest day was (17-12-2021), where the temperature reaches minimum 7°C at 7:00 in morning (Figs. 3 and 4).



Fig. 2 Location of The Study Area (Chaturbhuj Colony, Kankaria Maninagar, Ahmedabad, Gujarat, India) <https://earth.google.com/>

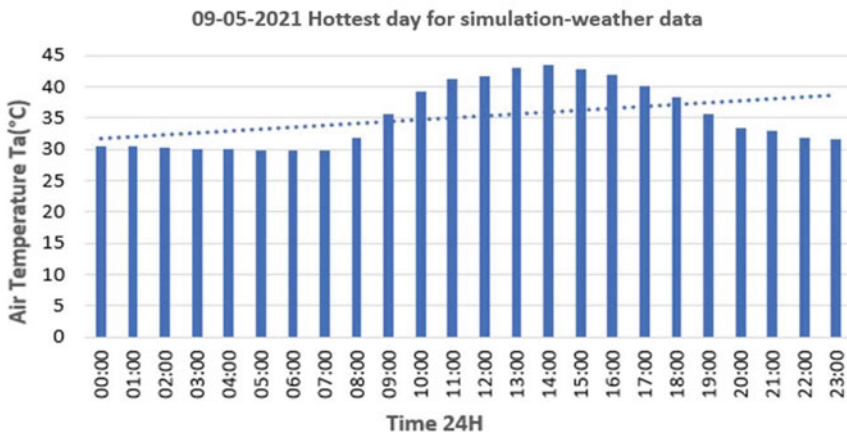


Fig. 3 Graph shows the air temperature for 24 h of 09th May 2021 hottest day

The flow chart of methodology shows that ENVI-met model was applied to conduct this study. The framework of ENVI-met software is shown in below flow chart.

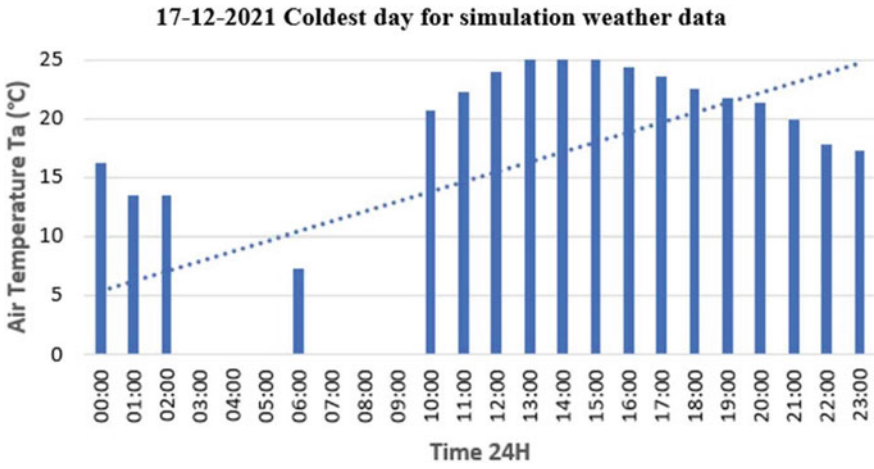
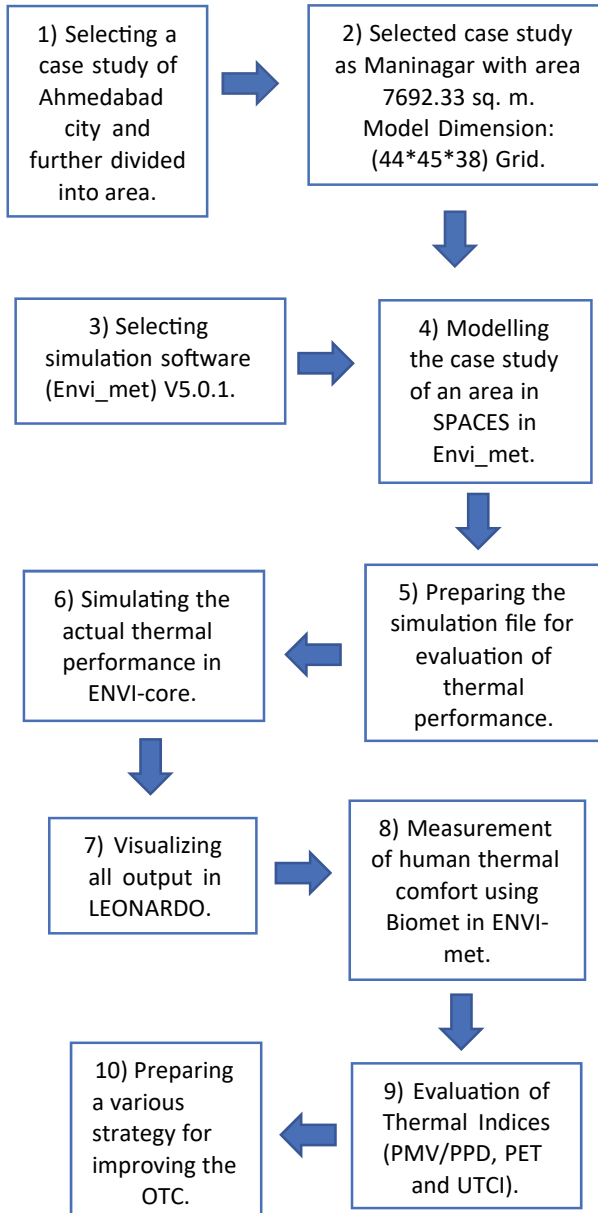


Fig. 4 Graph shows the air temperature for 24 h of 17th Dec 2021 coldest day



The below four different case scenarios were modelled in ENVI-met (SPACES) has a location of Maninagar area of Ahmedabad City, which has 7692.33 sq. km. area and has residential location coordinates of latitude $23^{\circ} 0' 4''$ and longitude $72^{\circ} 35' 45''$. Below, the various cases are mentioned below:

Four Different Case Scenario:

1. Base case scenario—It represents the current situation of area.
2. Number of trees at equal interval on all four side of corners—It means all four-side covered with oak tree and hedges on road divider (central verge)) and vegetation cover increased by 20% of the selected area.
3. Random Arrangement of tree near the building area—As mentioned earlier, vegetation cover increased by 20% of the selected area, and trees are arranged near the building area to provide proper shading and cooling effect to the building.
4. Façade and roof greening on building with some water bodies with base case scenario of tree arrangement—It means 100% of the roof and façade greening in the selected area covered with wall greening and roof greening with base case scenario of tree (means tree were same as it in case-1), and it also includes water bodies around 2–5% in this case.

The scaling of model = 1:1 (Actual Area) in ENVI-met model.

2.4 Preparing the Simulation file in ENVI-met Guide (.SIMX)

As discussed earlier, software simulations were performed in sunniest month as well as coldest month for the year 2021 which has the (24 h) simulation and below, and Table 1 shows the input details of meteorological parameters with various other parameters.

For Hottest Day—09-05-2021 Time and Date:

Meteorology—By Simple Forcing:

See Table 2.

For Coldest Day—17-12-2021 Time and Date:

See Table 3.

Meteorology—By Simple Forcing:

See Table 4.

Table 1 Shows the input data of time and date for the hottest day simulation

| | |
|----------------------------|------------|
| Start date | 09-05-2021 |
| Start time | 6:00 AM |
| Total simulations time (h) | 24 h |

Table 2 Shows the input data of meteorology for the hottest day simulation

| | |
|------------------------------------|----------------|
| Temperature °C. min. at 08:0 | 29 °C |
| Temperature °C. max. at 16:00 | 44 °C |
| Relative Humidity %. Min at 18:00 | 18 |
| Relative Humidity %. Max at 09:00 | 49 |
| Wind Speed | 3.15 m/s |
| Wind Direction | 355.00° (NW/E) |
| Roughness length | 0.010 m |
| Cloud Cover (low, medium and high) | 0, 4, 0 |

Table 3 Shows the input data of time and date for the coldest day simulation

| | |
|----------------------------|------------|
| Start date | 17-12-2021 |
| Start time | 6:00 AM |
| Total simulations time (h) | 24 h |

Table 4 Shows the input data of meteorology for the coldest day simulation

| | |
|------------------------------------|-----------------------|
| Temperature °C. min. at 07:00 | 7 °C |
| Temperature °C. max. at 16:00 | 26 °C |
| Relative Humidity %. Min at 08:00 | 6 |
| Relative Humidity %. Max at 12:00 | 53 |
| Wind Speed | 3.15 m/s |
| Wind Direction | 96.95° (NW/E) |
| Roughness length | 0.010 m |
| Cloud cover (low, medium and high) | 0, 4, 6 |
| CPU cores: | Multi core (Parallel) |
| Dynamic time step management | 2 s, 2 s, 2 s |

2.5 Model Validation

It is to check the accuracy of the model with real scenario. By comparing the outcomes of simulations with field observations, the ENVI-met model was validated. The measurements were done within the Maninagar area itself, where all meteorological data was recorded with an interval of 01:00 h' time and the instrument are located at coordinates of 23.02°N, 72.58°E, and data is download through CPCB Website.

Comparison of simulation (ENVI-met) results with measurements on 09 May 2021 for the hottest day (Summer)

See Fig. 5.

Here, you can see from the above scatter plot the RMSE value of air temperature between the measured and simulated data on 09 May 2021 for the 24 h was 0.2806

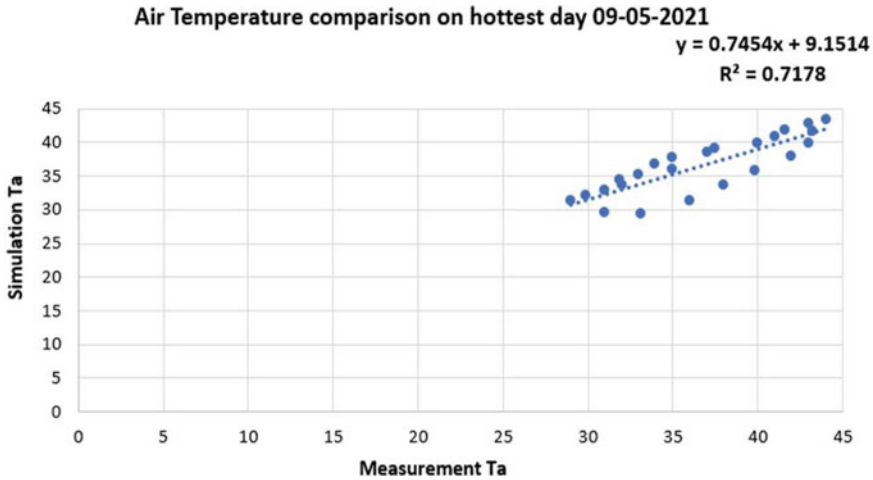


Fig. 5 Graph represents the scatter plots for the simulated and measured data of air temperature for the validation of model

and R^2 value is 0.71. The correlation coefficient between the two sets of data is 0.84, while the index of agreement between the two data set is 0.91 which is nearly to 1 which indicates the perfect match of the model. The data set which is used to create the scatter plot has only 24 h data and the data from simulations and measurements are compared to show the accuracy of the simulation results. The measured and simulation air temperature during 09th May 2021 are been compared for the 24 h, the patterns of air temperature between the measurement and the simulation are more or less the same, and the peak of Ta according to the measurement is 0.5–2 °C higher than according to the simulations.

Comparison of simulation (ENVI-met) results with measurements on 17 Dec 2021 for the coldest day (Winter)

See Fig. 6.

Here, you can see from the above scatter plot the RMSE value of air temperature between the measured and simulated data on 17 Dec 2021 for the 24 h was 0.8728 and R^2 value is 0.68. The correlation coefficient between the two sets of data is 0.83. While the index of agreement between the two data set is 0.86 which is nearly to 1 which indicates the perfect match of the model. The data set which is used to create the scatter plot has only 24 h data, and the data from simulations and measurements are compared to show the accuracy of the simulation results. The measured and simulation air temperature during 17 December 2021 are been compared, the patterns of air temperature between the measurement and the simulation are more or less the same, and the peak of Ta according to the measurement is 0.5–2 °C higher than according to the simulations.

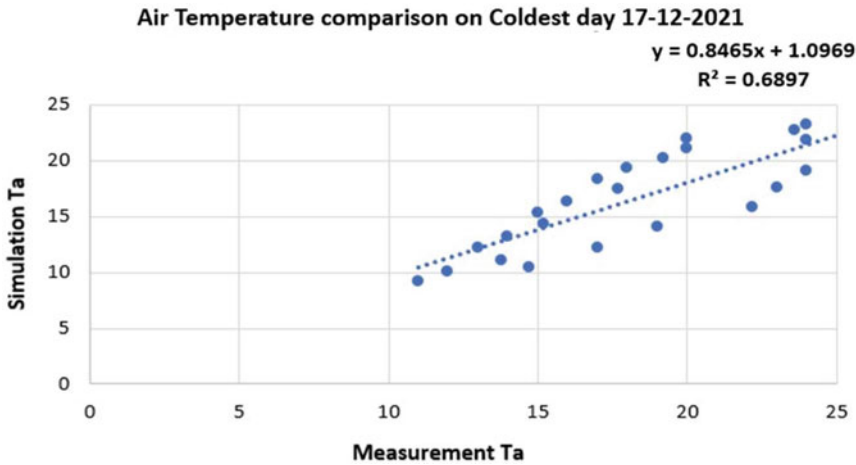


Fig. 6 Graph represent the scatter plots for the simulated and measured data of air temperature for the validation of model

3 Result and Discussion

The results were obtained by extracting raw output data using LEONARDO thematic mapping tools on the outdoor environment on particular location of four different case scenarios that were modelled in ENVI- met (SPACES) for Chaturbhuj colony, Kankaria Maninagar, Ahmedabad (Lat = 23.02 & Long = 72.60). The average air temperature and other environmental parameters for the particular site have been evaluated at 1.5 m height above ground level. There are total eight times simulations were performed in ENVI-core for four different case scenarios for coldest day in winter as well hottest day in summer for year 2021. (Means 4 times simulation performed for summer and 4 times simulation performed for winter) to get the better idea regarding how thermal comfort can affect for both the seasons. Each simulation takes times around 10–12 h for evaluating of the result.

Hot Summer Day (09-05-2021)

The result for the hot summer day (09-05-2021) where raw data is extract in thematic map tool LEONARDO is for a particular hour at 15:00 which reports the highest temperature of the particular day in a year.

Result for Air Temperature and Tmrt

See Fig. 7.

The overall variation from case-1 to case-4 of Ta reduction at 15:00 is around 1.520–1.120 °C, the overall variation from case-1 to case-4 of Tmrt reduction at 15:00 is around 6.236–1.02 °C; as you can see on below graph, the overall variation from case-1 to case-4 of PET reduction at 08:00 AM (Min) is around 2.607 °C to 4.904 °C, the overall variation from case-1 to case-2 of PET reduction at 15:00 (Max)

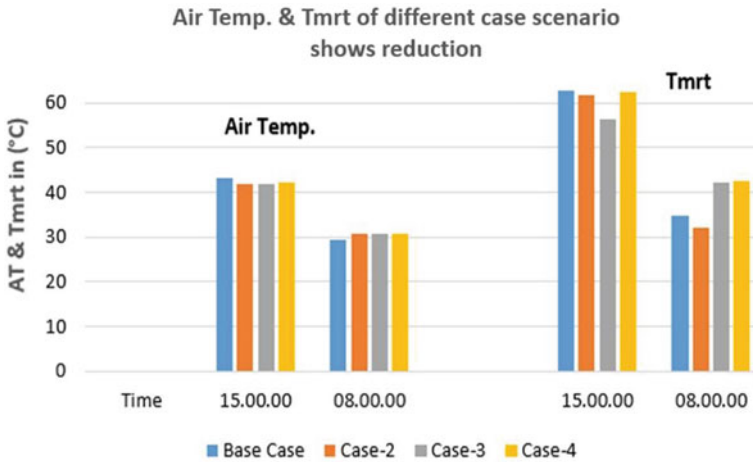


Fig. 7 Graph shows the air temperature and Tmrt patterns for all the cases at particular time 15:00 & 08:00

is around 0.363 °C, the overall variation from case-1 to case-4 of PMV reduction at 08:00 AM (Min) is around 0.1868 °C, the overall variation from case-1 to case-2 of PMV reduction at 15:00 (Max) is around 0.2635 °C, the overall variation from case-1 to case-4 of UTCI reduction at 08:00 AM (Min) is around 0.922–3.444 °C, and the overall variation from case-1 to case-2 of UTCI reduction at 15:00 (Max) is around 1.698–2.188 °C (Fig. 8).

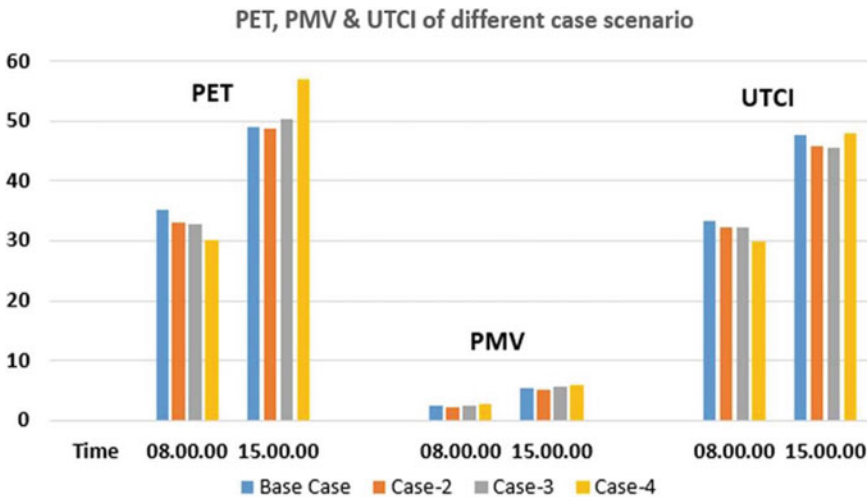


Fig. 8 Graph show the PET, PMV and UTCI thermal indices patterns for all the cases at particular time 15:00 & 08:00

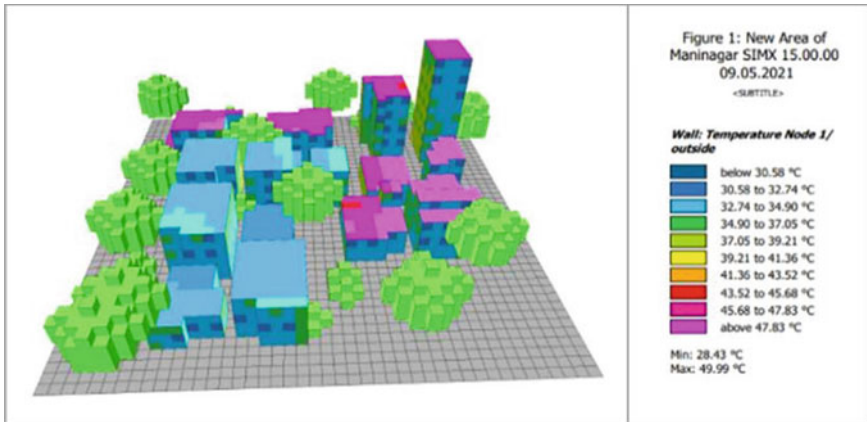


Fig. 9 Image shows the wall: temp node 1/outside at 15:00 of study area in 3d view

Result of roof and Façade greening

See Fig. 9.

The building which has roof and façade greenings has a wall greening material: green + mixed substrate & roof greening materials: only green is higher in temperature (hotter) as compared to the building which has wall greening material: green + mixed substrate and roof greening material: green + sandy loam substrate. It has a difference around 1.5 °C means green + sandy loam substrate is cooler than only green roof and has a variation around 1–3 °C. It provides more cooling effect on roof. (Wall: Air Temp. in front of façade).

Cold Winter Day (17-12-2021)

The result for the cold winter day (17-12-2021) where raw data is extract in thematic map tool LEONARDO is for a particular hour at 07:00 which reports the lowest temperature of the particular day in a year.

Result for Air Temperature and Tmrt

See Fig. 10.

The overall variation (temperature increases) from case-1 to case-4 of Ta at 07:00 on 17-12-2021 in winter is around 0.6657–0.6822 °C, and the overall variation (temperature increases and decreases) from case-1 to case-4 of Tmrt at 07:00 on 17-12-2021 in winter is around 1.7017 °C (increase) to 0.6021 °C (decrease).

3.1 Strategies Planned During the Study

As per literature review, the study has been conducted hypothetically in Envi_met (SPACES) model with have been planned from simulated results by taking two

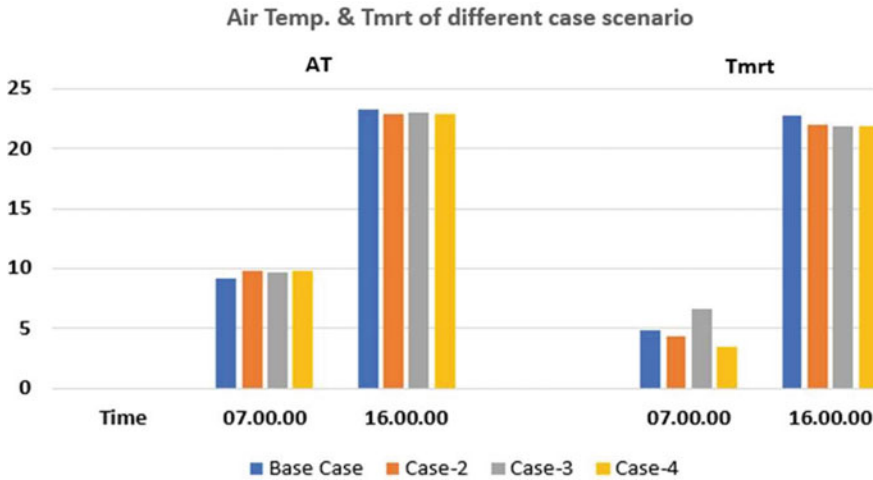
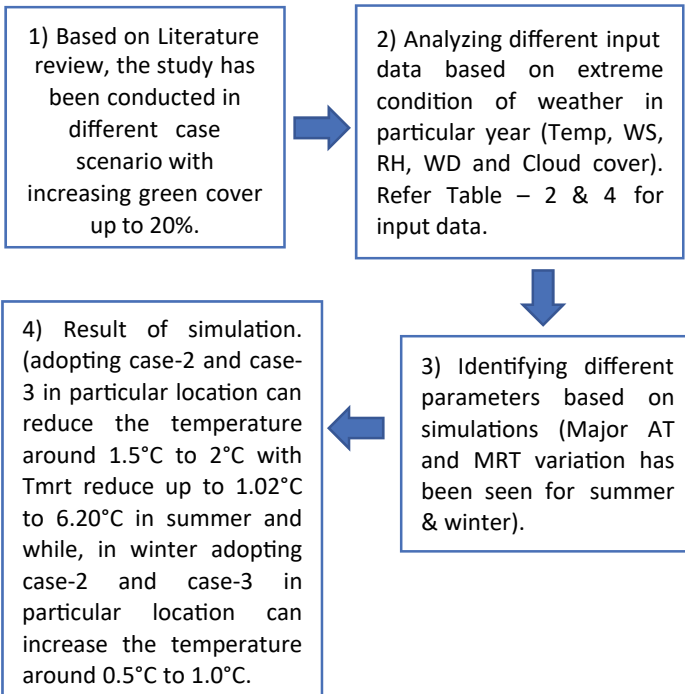


Fig. 10 Graph show the air temperature and patterns for all the cases at particular time 16:00 & 07:00

extreme condition in summer & winter. Below, methodology chart shows the different stages of analysis.



The simulated results (for a typical summer day 09 May 2021 at 15:00) show that the suggested strategies have an effect on OTC.

1. The building which has roof and façade greenings has a wall greening material: green + mixed substrate & roof greening materials: only green is higher in temperature (hotter) as compared to the building which has wall greening material: green + mixed substrate and roof greening material: green + sandy loam substrate. It is due to sandy loam substrate which is made up of soil along with varying amount of silt and clay.
2. As a design consideration, adopting or implementing case-4 (Façade and roof greening) in a hot humid climate can decrease the temperature of building at typical hottest day in a summer, and it has a more cooling effect than normal construction material used in buildings.
3. Increasing vegetation around 20% means: as a solution, planting a oak tree (which has a same significance of neem tree) on all four side of location or planting trees on the roadside (Road Arboriculture) means adopting case-2 in particular location can reduce the temperature around 1.5 °C and can provide more shade during the daytime as well it will help to reduce long and short wave radiation (mean radiant temperature) up to 1.02 °C and also thermal indices such as PET reduce around 0.37 °C, PMV 0.25 °C and UTCI up to 2.20 °C.
4. The 4 m hedges which was planted on road divider (central verge) can act as wind shielding to improve outdoor thermal comfort and reduce the wind speed as well. It can also be used to protect the soil from erosion and acts as a barrier to prevent accident and absorb sound to prevent from noise pollution.
5. Wind shielding/sheltering can be utilized to increase outdoor thermal comfort in a location where people like to congregate, such as café, courtyard and garden.
6. The key aim to increase the vegetation (green cover) to certain extent in (%) is to reduce the wind speed and air temperature as well.
7. As a solution, increasing vegetation around 20% means in case-3 that is random arrangement of the tree near the building area can be adopted or implemented to improve outdoor thermal comfort of a residential area.
8. As a design consideration, case-3 not only provides shade from radiation but also provides cooling effect to the near building area. It reduced the temperature around 1.5 °C and also helps to reduced short and long wave radiation (mean radiant temperature) up to 6.20 °C and also thermal indices such as PMV 0.240 °C and UTCI up to 2.19 °C.
9. A heaven tree (known as *Ailanthus excelsa*) planted near the building area can alone provide more shade to the occupant and reduce the air temperature in front of façade and has better effect on outdoor thermal comfort. It has one major benefit that is the most effective tree for absorbing suspended particulate matter.

The simulated results (for a typical coldest day 17 December 2021 at 07:00 AM) show that the suggested strategies have an effect on OTC.

10. As a design consideration, planting an oak tree (which has a same significance of neem tree) on all four side of location or planting trees on the roadside (Road Arboriculture) with deciduous tree means adopting case-2 can increase the temperature up to 0.5 °C to 1.0 °C and can allow solar radiation as well; here, MRT has been decreased around 0.6 °C, and also thermal indices such as PET increase approx. 0.04 °C, PMV approx. 0.36 °C and UTCI approx. 1.21 °C.
11. As a design consideration, adopting case-3 random arrangement of tree near the building area. It has a coniferous tree like pine, palm and conic, and large trunk improves heat comfort than broadleaves tree. The case-3 has an effective in increasing the temp up to 1.0 °C, and MRT has been increased up to 1.80 °C.

4 Conclusion

This research uses the ENVI-met model for microclimate numerical simulation to evaluate how different case scenarios affect the study area with environmental parameters consisting of air temperature, T_{mrt} and thermal indices along with PMV, PET and UTCI. Various heat mitigation strategies were planned during the study based on simulation results that were visualized as thematic map in LEONARDO for 24 h for the extreme condition that is on hottest day as well coldest day. The model shows the accuracy with simulated and measured environmental parameters for the validation. The validated model was used to investigate four case scenarios. (1) Base case scenario, (2) Number of trees at equal interval on all four side of corners, (3) Random arrangement of tree near the building area and (4) Façade and roof greening on building with some water bodies with base case scenario of tree arrangement.

This various heat mitigation strategies can be adopted in Ahmedabad City for improving outdoor thermal comfort, with Ahmedabad being one of the most developing cities of India, it is not economical nor it can be simple to implement high-tech urban design in a pre-existing area in a densely populated area, and hence, such issues can be addressed with adequate urban planning and other cost-effective measures. At the city level of Ahmedabad, the study provides a better understanding of heat mitigation strategies on human thermal comfort and the findings of this research provide the stakeholders with finer suggestion for improving outdoor thermal comfort environment of residential area and to developed sustainable cities, and also, it has direct impact on the health and wellbeing of occupants of outdoor spaces.

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