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Simulation-Based Evaluation of Green Infrastructure Strategies for Urban Heat Island Mitigation using ENVI-Met

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Abstract

Urban areas are increasingly experiencing elevated air temperatures due to land-use variations, densely built-up areas and reduced vegetation cover. Although many previous studies have identified vegetation as a critical factor in reducing Urban Heat Island (UHI), the micro-scale effects of urban morphology, surface materials, built-up structures and vegetation distribution remain insufficiently explored in developing urban contexts. This study presents a simulation-based approach to assess the effect of green infrastructure strategies on urban microclimate conditions in a tropical urban environment. A detailed three-dimensional model of the study area is developed using ENVI-met by integrating high-resolution satellite images, geotagged field observations, and on-site measurements. Key urban features such as building geometry, surface materials, orientation of roads and bridges and vegetation distribution are accurately depicted. Meteorological inputs such as air temperature, relative humidity and wind speed from regional weather records are validated with field data. Various green cover and shading conditions are often simulated to analyse their impact on surface-air temperature and outdoor thermal comfort. The results indicate that the implementation of urban greenery effectively in mitigating urban heat stress while improving small-scale climatic scenarios. The outcomes highlight the incorporation of vegetation-based measures and shading solutions under the urban planning system to promote sustainable development in progressive urban areas.

Keywords: Urban Heat Island, ENVI-met, Urban Microclimate, Green Infrastructure, Thermal Comfort, Simulation, Vegetation, Urban Planning

1. INTRODUCTION

Rapid urbanization in developing regions, particularly in tropical countries such as India, has resulted in a significant transformation of natural landscapes into densely built environments dominated by concrete, asphalt, and other impervious materials. This transformation has changed the natural energy balance of urban areas, leading to increased heat absorption during the daytime and reduced cooling during nighttime. Similarly, urban regions experience a localized warming phenomenon known as the Urban Heat Island (UHI) effect. This phenomenon not only affects environmental conditions but also has significant hazards for human health, energy consumption, and urban sustainability.

Green infrastructure has emerged as a critical strategy for mitigating the harmful impacts of UHI. It includes the combination of natural and semi-natural elements such as trees, parks, green roofs and vegetated surfaces within urban environments. These elements contribute cooling effects through mechanisms such as shading, evapotranspiration, and modification of surface albedo. In tropical climates like in Kerala, where high temperature and humidity dominates, the role of green infrastructure becomes even more significant in improving thermal comfort and enhancing urban quality of life.

Although the benefits of green infrastructure recognized, its quantitative evaluation in urban environments remains difficult due to the complexity of microclimate interactions. Traditional field measurements are often limited in spatial and temporal scope. Therefore, simulation-based tools such as ENVI-met have gained importance for their ability to model complex interactions between urban geometry, vegetation, and atmospheric conditions. This study aims to evaluate the effectiveness of green infrastructure strategies using ENVI-met simulation in a representative urban area of Kollam, Kerala.

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2. LITERATURE REVIEW

A comprehensive review of existing literature indicates that urban microclimate is governed by a complex interaction of factors including urban geometry, surface material properties, vegetation distribution, and atmospheric conditions. Rapid urbanization has led to an increase in impervious surfaces such as asphalt and concrete, which significantly alter the surface energy balance and contribute to elevated urban temperatures. Studies based on remote sensing and land surface temperature analysis have demonstrated a strong correlation between reduced vegetation cover and increased urban heat intensity, particularly in rapidly developing tropical regions. These findings highlight the critical role of land-use changes and built-up expansion in intensifying urban heat island (UHI) effects.

Vegetation has been widely recognized as one of the most effective natural solutions for mitigating urban heat. Several studies have emphasized the cooling potential of green infrastructure elements such as trees, green walls, and urban parks. For instance, research on vertical greening systems has shown that green walls can significantly reduce ambient temperature and improve thermal comfort by providing shading and enhancing evapotranspiration. Similarly, studies on urban parks have demonstrated that larger green spaces with dense vegetation and integrated water features act as cooling islands within cities, reducing surrounding air temperatures and improving microclimatic conditions. The effectiveness of vegetation is strongly influenced by factors such as canopy density, spatial distribution, and plant characteristics, which determine the extent of shading and moisture exchange with the atmosphere.

Simulation-based approaches have gained prominence in recent years for analysing urban microclimate due to their ability to model complex interactions between urban elements and atmospheric processes. ENVI-met, in particular, has been extensively used for high-resolution three-dimensional simulation of microclimatic conditions. Several studies have validated the accuracy and reliability of ENVI-met by comparing simulation outputs with field measurements and UAV-based observations, confirming its effectiveness as a tool for urban climate analysis. Research has also demonstrated that ENVI-met can accurately simulate parameters such as air temperature, wind flow, humidity, and surface heat exchange, making it suitable for evaluating the impact of urban design interventions.

Recent literature further emphasizes the importance of integrated and multi-layered strategies for urban heat mitigation. Studies have shown that combining vegetation with water bodies and thermally efficient materials produces significantly greater cooling effects compared to single interventions. Water bodies contribute to evaporative cooling, while reflective and permeable materials reduce heat absorption and enhance heat dissipation. Additionally, the spatial arrangement of these elements plays a crucial role in determining their effectiveness. Research on urban layout optimization and three-dimensional modelling highlights that factors such as building orientation, spacing, and height influence airflow patterns, shading, and heat distribution within urban environments. Moreover, advanced studies have explored the integration of microclimate simulation with building energy models and urban planning frameworks, emphasizing the need for a holistic approach to sustainable development. The use of scenario-based simulations allows researchers to evaluate different design alternatives and identify optimal strategies for improving thermal comfort. These approaches are particularly relevant in high-density urban areas, where even minor modifications in layout and vegetation placement can lead to significant improvements in microclimatic performance.

Overall, the literature consistently establishes that green infrastructure, when strategically integrated with urban design and supported by simulation-based evaluation tools such as ENVI-met, can effectively mitigate urban heat island effects and enhance outdoor thermal comfort. The insights derived from previous studies provide a strong foundation for the present research, guiding the selection of methodology, modelling approach, and design interventions aimed at improving urban microclimate in a tropical context.

3. METHODOLOGY

3.1. GENERAL

The present study adopts a simulation-based analytical approach to evaluate the effectiveness of green infrastructure strategies in reducing UHI effects within a tropical urban environment. The methodology combines field observations, computational modelling and scenario-based simulation using ENVI-met to examine the microclimatic variations at a localized scale. This integrated approach enables a systematic evaluation of the interactions between urban geometry, surface materials, vegetation, and atmospheric conditions, thereby providing a dependable foundation for climatic-responsive urban planning and design.

3.2. STUDY AREA

The selected study area is Chathanoor Junction in Kollam district, Kerala (Fig 1), which represents a rapidly urbanizing region represented by dense built-up structures, extensive impervious surfaces and limited vegetation cover. These conditions make the area highly vulnerable to heat accumulation and microclimatic imbalance. A model domain of 100 m x100 m was defined to represent the study area, which is suitable for neighbourhood-scale microclimate simulation using ENVI-met. These domain was divided into a uniform grid system to accurately capture spatial variations in temperature, airflow and surface interactions.

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The study began with a detailed site analysis to understand the physical and environmental factors influencing heat accumulation. Field observations indicated that the study area is dominated by asphalt roads, concrete pavements, closely spaced buildings, and minimal vegetation. These factors contribute significantly to increased surface temperatures and reduced thermal comfort. Observations also highlighted the influence of urban geometry on airflow patterns was visible, with densely built area showing restricted ventilation and higher heat retention.

Following the site study, extensive data collection was carried out through multiple field visits. Measurements and observations were recorded for building dimensions, floor heights, road widths, surface materials and vegetation types. Climatic parameters such as air temperature and windspeed were obtained using field instruments and validated with local meteorological data. The collected data was systematically arranged and used to develop an accurate representation of the study area within the ENVI-met simulation environment.

Fig 1: Chathanoor junction

3.3. SOFTWARE IMPLEMENTATION

3.3.1. BASE SCENARIO

The modelling process was initiated by creating a project workspace in ENVI-met, where the study domain and simulation parameters were defined. The base scenario was developed to replicate the existing urban conditions of the study area (Fig 2). This involved digitizing building geometries, defining road networks and assigning appropriate surface materials such as asphalt and concrete, which are known for their high heat absorption and low reflectivity. Vegetation in the base scenario was kept minimal to reflect actual site conditions. Additionally, receptor points were strategically placed within the model to record microclimate parameters at specific locations.

The simulation setup included defining meteorological inputs such as air temperature, relative humidity, windspeed, and wind direction over a specified time period. These inputs were carefully selected to represent typical climatic conditions of the region and were kept consistent across all scenarios to ensure a reliable comparison. The simulation was carried out using ENVI-met, which models the interactions between surfaces, vegetation, and atmospheric conditions.

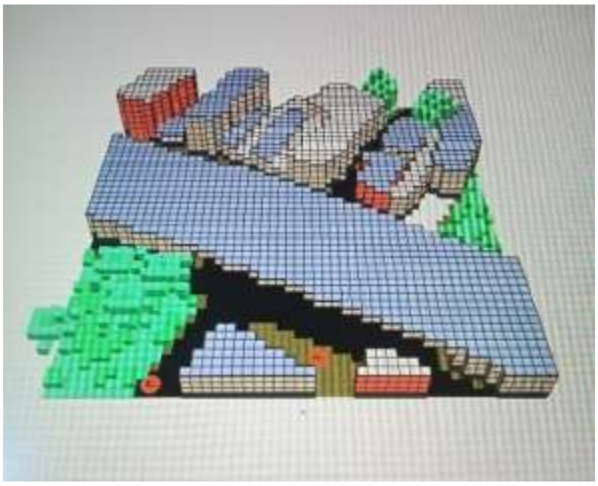

Fig 2: Base model

3.3.2. MODIFIED SCENARIO

To evaluate the effectiveness of green infrastructure, a modified scenario was developed by including sustainable design interventions within the same model domain (Fig 3). Vegetation elements such as trees, grass and hedges were introduced to enhance shading and evapotranspiration. Trees with medium to dense canopy were selected to maximize cooling effects. In addition, a water body in the form of a pond was included to promote evaporative cooling. Surface materials were also modified to improve thermal performance by increasing reflectivity and permeability, thereby reducing heat absorption. These interventions were strategically arranged to target high-temperature areas and enhance overall cooling efficiency.

Fig 3: Modified model

3.3.3. COMPARATIVE ANALYSIS

Both base and modified scenarios were simulated under identical environmental conditions to maintain consistency in comparison. The simulation outputs were processed and detailed spatial visualization of microclimatic parameters such as air temperature and wind flow. Temperature distribution maps were generated to identify heat concentration zones, while receptor data was extracted for quantitative analysis of temperature variations at specific locations.

The comparative analysis between the base and modified scenarios was conducted to evaluate the impact of the proposed green infrastructure strategies. Both spatial and numerical data were examined to identify trends in temperature reduction and airflow improvement. The analysis focused on understanding the role of vegetation, water bodies, and surface modifications in influencing microclimate conditions. This systematic workflow from site analysis and data collection to modelling, simulation, and evaluation ensures that the study provides a comprehensive and scientifically reliable assessment of urban microclimate.

4. RESULTS AND DISCUSSION

4.1. GENERAL

The simulation outputs generated from the ENVI-met model and visualized using the LEONARDO module, provide a comprehensive understanding of the microclimatic variations within the selected study area under both base and modified scenarios. The results clearly demonstrate the spatial distribution of air temperature and highlight the effectiveness of green infrastructure interventions in mitigating UHI effects.

4.2. BASE SCENARIO OUTPUT

In the base scenario, representing the existing site conditions, higher temperature zones are usually observed in regions dominated by asphalt roads, concrete pavements, and densely built structures. These materials are characterized by high thermal storage capacity and low reflectivity, leading to increased absorption of solar radiation during daytime and gradual release of heat into the surrounding environment. Similarly, significant heat accumulation occurs, especially along road corridors and open paved areas with minimal shading. The simulation results indicates that the maximum air temperature in the base scenario reaches approximately 32.30°C, especially in the areas exposed to direct solar radiation and lacking vegetative cover. This highlights the critical role of impervious surfaces and urban geometry in influencing thermal conditions (Fig 4).

4.3. MODIFIED SCENARIO OUTPUT

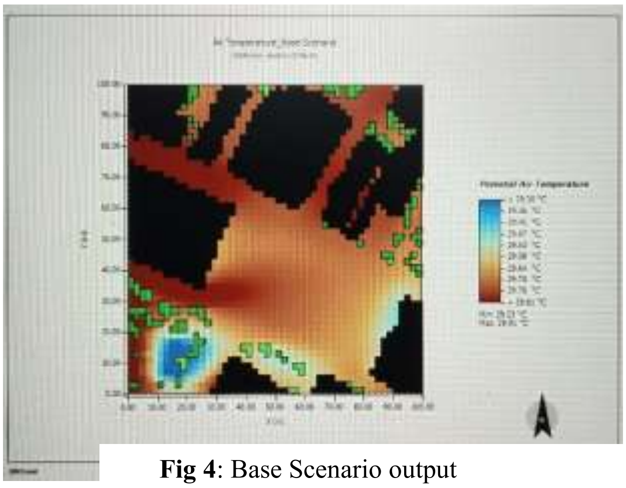

Fig 4: Base Scenario output

In contrast, the modified scenario shows a noticeable improvement in thermal conditions across the study area (Fig 5). The introduction of green infrastructure elements, including trees, grass surfaces, hedges, and a water body, significantly changed the microclimatic behaviour of the environment. The simulation results reveal that the maximum air temperature in the modified scenario is reduced to approximately 30.89°C, including a temperature reduction in the range of 1.4°C-2.0°C compared to the base case. This represents an approximate reduction of 4-6% in peak temperature values, which is significant at the micro-scale level.

The observed cooling effect can be explained through three primary mechanisms. Firstly, shading provided by trees plays a crucial role in reducing direct solar radiation on ground and built surfaces. This minimizes heat absorption and prevents excessive temperature rise in exposed areas. Secondly, evapotranspiration from vegetation contributes to cooling by converting sensible heat into latent heat, thereby lowering ambient air temperature. Thirdly, the introduction of a water body enhances evaporative cooling, particularly in its immediate surroundings, by facilitating heat exchange between water and air. These combined effects significantly improve thermal performance and reduce heat stress within the study area.

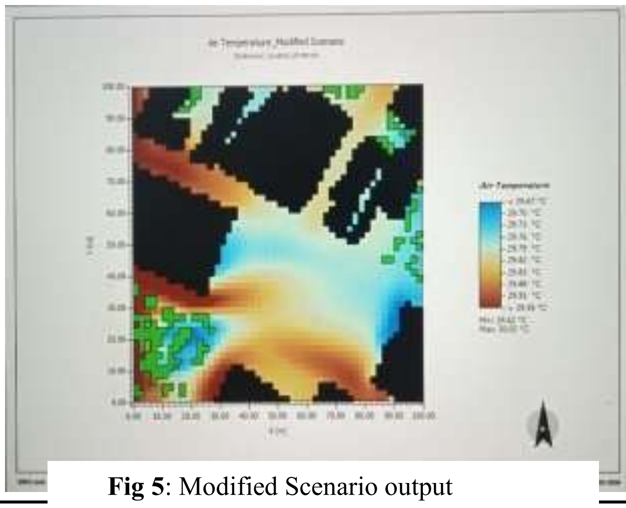

Fig 5: Modified Scenario output

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4.4. OUTPUT INTERPRETATION

A detailed analysis of receptor data supports these findings by providing quantitative data on temperature variations at specific locations. The results show a consistent reduction in air temperature across all monitored points, including areas near roads, buildings, open spaces, and vegetated zones. However, the magnitude of temperature reduction varies depending on the amount of green infrastructure elements. The highest reduction is observed in areas with dense vegetation cover, particularly near tree canopies, where shading and evapotranspiration effects are most effective. For instance, temperatures near tree-covered regions decreased from approximately 32.20°C in the base scenario to around 30.89°C in the modified scenario (Table 1). Similarly, areas near vegetation zones pointed a noticeable reduction, while built-up and road areas showed moderate improvements due to indirect cooling effects.

The graphical comparison of temperature variation across different receptor locations further indicates the effectiveness of the modified scenario (Fig 6). The base scenario consistently records higher temperature values across all points, whereas the modified scenario demonstrates a uniform reduction in temperature, particularly in areas influenced by vegetation and shading. The maximum temperature drop is observed in areas with increased tree cover, highlighting the important role of vegetation in urban cooling. Although minor variations exist due to differences in local airflow and surface conditions, the overall trend clearly favours the modified scenario.

From an engineering perspective, the results confirm the effectiveness of combined green infrastructure strategies in improving urban microclimate. The combination of vegetation, water bodies, and improved surface materials creates a synergistic cooling effect. The reduction in temperature over road and paved areas, although comparatively smaller, indicates that material modification also contributes to thermal improvement by reducing heat absorption and increasing reflectivity. This indicates that even partial interventions can lead to measurable improvements in urban thermal performa

Moreover, the spatial variation in temperature reduction highlights that microclimatic improvements are highly influenced by local conditions such as vegetation density, shading intensity, and surface characteristics. Areas with dense vegetation and water features exhibit greater cooling, while heavily built-up zones show relatively lower improvements due to thermal inertia and heat retention properties. This underlines the need for location-specific planning rather than uniform implementation of mitigation strategies.

The results obtained from this study are consistent with findings reported in previous research, thereby validating the reliability of the ENVI-met simulation model. Studies have shown that vegetation-based interventions significantly reduce urban temperatures and improve thermal comfort through mechanisms similar to those observed in the present study. The agreement between present results and existing literature strengthens the credibility of the adopted methodology.

Overall, the results clearly demonstrate that the implementation of green infrastructure strategies leads to significant improvements in urban microclimate by reducing air temperature and enhancing thermal comfort. The study confirms that simulation-based evaluation using ENVI-met provides a reliable and effective approach for assessing urban heat mitigation strategies and supports the development of sustainable and climate- responsive urban planning solutions.

A) TABLE LAYOUT

Location	Base case (°C)	Modified case(°C)
Tree	32.3	30.89
Road	31.7	31.49
Open Area	32.12	31.18
Buildings	31.27	31.18
Near Vegetation	32.21	31.91

Table 1: Base case vs Modified case

B) GRAPH

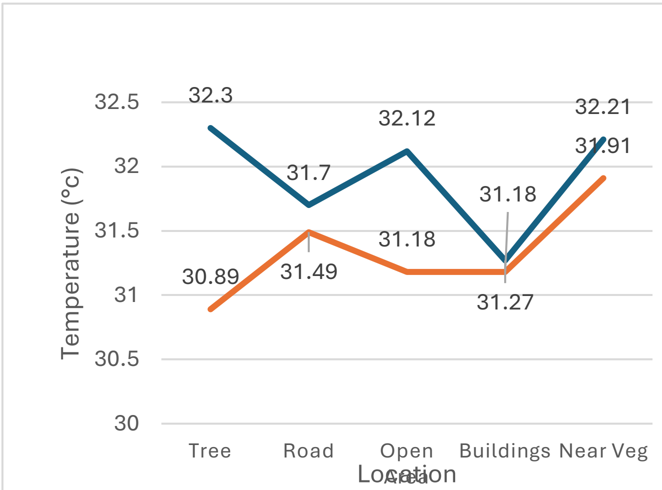

Fig 6.: Base case vs Modified case

5. CONCLUSION

The present study effectively evaluates the role of green infrastructure strategies in mitigating urban heat island (UHI) effects through detailed ENVI-met simulation for representative urban area at Chathanoor Junction, Kollam. The analysis was conducted by developing two scenarios, namely the base case representing existing site conditions and a modified case incorporating sustainable interventions such as increased vegetation cover, introduction of a water body, and modification of surface materials. The comparative results clearly indicate that the modified scenario achieves a consistent and measurable improvement in urban microclimatic conditions.

A significant reduction in air temperature, was observed across the study area in the modified scenario. This reduction confirms the effectiveness of integrated green infrastructure in regulating urban thermal conditions. The most significant cooling effects were recorded in areas with dense vegetation and in near to the introduced water body, highlighting the combined influence of shading, evapotranspiration and evaporative cooling processes. Vegetation plays a critical role by reducing solar radiation and facilitating moisture exchange, thereby reducing sensible heat and improving ambient air temperature. Similarly, the inclusion of a water body contributes to localized cooling through latent heat exchange, enhancing thermal comfort in surrounding areas. In addition to vegetation and water elements, the modification of conventional surface materials also contributed to thermal improvement. The use of more reflective and permeable materials reduced heat absorption and storage, thereby minimizing the release of heat into the surrounding environment. Although the cooling effect in built-up and road areas was comparatively moderate, the overall reduction across all receptor locations confirms that even partial interventions can lead to meaningful improvements in urban thermal performance. The variation in temperature reduction across different zones further indicates that microclimatic behaviour is highly dependent on spatial configuration, surface characteristics and near to cooling elements, pointing out the need for strategic and location -specific planning.

The findings of this study strongly reinforce the importance of mixing green infrastructure within urban environments to address the challenges associated with rapid urbanization and increasing heat stress. The results works well with established research in the field, thereby validating both the effectiveness of the proposed strategies and the reliability of ENVI-met as a simulation tool for urban microclimate assessment. The study provides a scientifically grounded framework that can support urban planners, engineers and policymakers in designing sustainable and climate -responsive urban spaces, particularly in tropical regions such as Kerala.

Furthermore, the research highlights the significance of simulation-based approaches in evaluating urban design interventions prior to implementation. ENVI-met proves to be a powerful tool for analysing complex interactions between urban form, vegetation and atmospheric conditions, enabling informed decision-making for heat mitigation strategies. The ability to model and compare different scenarios enhances the efficiency and accuracy of planning process, making it a accurate and precise tool in sustainable urban development.

Future research can focus on extending the scope of the study by incorporating seasonal simulations to assess the performance of green infrastructure under varying climatic conditions. The inclusion of advanced thermal comfort indices such as Physiological Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI) using BIO-met can provide a deeper comprehensive understanding of human thermal comfort. Additionally, validation of simulation results through real-time field measurements can further improve the accuracy and reliability of the model. Exploration of additional strategies such as green roofs, cool pavements and urban shading devices can also enhance the applicability of the findings and contribute to the development of more resilient urban environments.

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