RESEARCH ARTICLE

JENER Journal of Empirical and Non-Empirical Research
Volume 2, Issue 2, Page 434-438 | Article No. 52
DOI: 10.4898/jener.v2i2.a52
ISSN: 7895-9216
Journal homepage: https://jenerjournal.com
Journal email: editor@jenerjournal.com

JENER Journal
JENER Journal of Empirical and Non-Empirical Research

Envi-met Assessment of Vegetation-Centric Outdoor Thermal Conditions on Northeast Nigerian Campuses: A Case Study at Yelwa Campus, Abubakar Tafawa Balewa University Bauchi

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ARTICLE INFORMATION

Article history:
Published: February 2026

Keywords:
ENVI-met Simulation
Campus Outdoor Environment
Outdoor Thermal Comfort
Vegetation Planning
HOBO Data Logger

ABSTRACT

Outdoor thermal discomfort poses a major challenge to the usability and environmental quality of university campuses in Northeast Nigeria due to extensive impervious surfaces, declining vegetation cover, and prolonged exposure to extreme climatic conditions. Although vegetation is widely recognised as an effective passive cooling strategy, its microclimatic performance is strongly influenced by spatial configuration, density, and interaction with surrounding built elements. In many campuses, vegetation is implemented without prior performance evaluation, resulting in limited thermal benefits. This study adopts a quantitative research approach using ENVI-met microclimate simulation to assess vegetation-centric outdoor thermal conditions at the Yelwa Campus of Abubakar Tafawa Balewa University, Bauchi. Existing and vegetation-enhanced scenarios were simulated to analyse variations in air temperature, mean radiant temperature, wind speed, and surface heat accumulation. Comparative analysis reveals that strategically planned vegetation significantly improves outdoor thermal comfort. The findings highlight the importance of simulation-led landscape planning as a climate-responsive approach to campus outdoor design in hot, semi-arid environments.

1. Introduction

Outdoor spaces play a critical role in supporting academic activities, social interaction, and pedestrian circulation within university campuses. In hot and semi-arid regions like Northeast Nigeria, however, extreme thermal conditions significantly limit outdoor usability and negatively affect users' comfort, wellbeing, and overall productivity (Santamouris, 2020; Emmanuel & Johansson, 2021; Oke et al., 2021; Adegun & Adedeji, 2021; Morakinyo et al., 2022; Adebayo et al., 2024). The rapid urbanization and expansion of built environments have led to reduced green spaces, increasing urban heat island effects and exacerbating heat stress during peak seasons, where air temperatures often exceed 35°C (Yang et al., 2020; Taleghani et al., 2022; Zhang et al., 2021). Vegetation serves as a passive cooling mechanism through shading, evapotranspiration, and wind modulation, but its efficacy requires precise assessment through advanced simulation tools like ENVI-met to optimize species selection, placement, and density (Shashua-Bar et al., 2020; Klemm et al., 2022; Lenzholzer et al., 2023; Peng et al., 2023). Without such evaluations, implementations often result in suboptimal thermal benefits, wasted resources, and persistent discomfort. This study focuses on quantifying the thermal benefits of vegetation enhancements at Yelwa Campus, Abubakar Tafawa Balewa University (ATBU) Bauchi, using a quantitative approach to inform climate-responsive campus design. The campus, located at coordinates 10°19'N 9°50'E, spans approximately 200 hectares with predominant hard surfaces and sparse vegetation cover (less than 20% canopy), highlighting the urgency for targeted interventions (Morakinyo, 2020; Aljahdaly et al., 2023).

1.1 Problem Statement

Despite increasing awareness of climate-responsive design, outdoor thermal comfort remains inadequately addressed in campus planning in Northeast Nigeria. Vegetation is frequently introduced without quantitative performance assessment, resulting in persistent thermal stress, reduced outdoor usability, and potential health risks for students and staff (Rahman et al., 2021; Chen et al., 2022; Fei et al., 2024; Al-Saffar, 2024). Field measurements using HOBO data loggers revealed baseline air temperatures averaging 34.2°C in dry seasons, underscoring the need for simulation-driven strategies to mitigate heat accumulation from built surfaces and low vegetation density (Adegun & Adedeji, 2021; Morakinyo et al., 2022).

1.2 Aim and Objectives

This study aims to quantitatively assess vegetation-centric outdoor thermal conditions at ATBU Yelwa Campus using ENVI-met simulation. The objectives are to: assess existing thermal conditions through field data and modeling; simulate vegetation-enhanced scenarios with increased canopy cover; compare thermal parameters such as air temperature, mean radiant temperature, wind speed, and surface heat accumulation; and evaluate vegetation effectiveness in improving comfort levels across key campus zones (Crank et al., 2021; Chen et al., 2023; Santamouris et al., 2024).

2. Literature Review

Recent studies emphasize the multifaceted influences on outdoor thermal comfort, including air temperature, mean radiant temperature (MRT), wind speed, relative humidity, and surface properties, with MRT often being the dominant factor in hot climates due to its impact on radiant heat exchange (ISO 7730, 2021; Taleghani et al., 2022; Yang et al., 2020; Zhang et al., 2021; Zhang et al., 2025). In arid and semi-arid environments, urban heat islands amplify these effects, necessitating passive strategies like vegetation integration to counteract rising temperatures and improve human comfort in outdoor spaces (Santamouris, 2020; Emmanuel & Johansson, 2021; Oke et al., 2021). For instance, research in urban climates has shown that impervious surfaces contribute significantly to heat retention, leading to elevated thermal stress that can be mitigated through strategic greening initiatives (Adegun & Adedeji, 2021; Morakinyo et al., 2022; Adebayo et al., 2024). These studies collectively highlight how microclimatic factors interact in complex ways, particularly in densely built areas like university campuses, where pedestrian exposure to heat is prolonged during daily activities. Furthermore, the integration of simulation tools has become essential for predicting these interactions, allowing planners to test scenarios before implementation and avoid costly errors in landscape design (Crank et al., 2021; Chen et al., 2023; Santamouris et al., 2024).

2.1 Vegetation and Outdoor Thermal Regulation

Vegetation reduces heat stress by intercepting solar radiation, promoting evapotranspiration, and facilitating convective cooling, with tree canopies shown to lower air temperatures by up to 3-4°C and MRT by 7-65°C in various urban settings (Morakinyo et al., 2021; Peng et al., 2022; Klemm et al., 2022; Lenzholzer et al., 2023; Morakinyo, 2020; Aljahdaly et al., 2023; Fei et al., 2024; Al-Saffar, 2024; Karunathilake et al., 2024). In Nigerian universities, tree shading has been effective in mitigating both indoor and outdoor temperatures, providing empirical evidence that native species can adapt well to local conditions while offering substantial cooling benefits (Shashua-Bar et al., 2020; Chen et al., 2022; Ameen et al., 2024). Beyond temperature reduction, vegetation enhances airflow patterns, which is crucial in low-wind environments, and contributes to long-term ecological benefits such as carbon sequestration and biodiversity support (Wu et al., 2025; Erker & Townsend, 2020). Comparative analyses from tropical and arid regions, such as those in Riyadh and Mosul, demonstrate that optimized vegetation layouts not only improve physiological equivalent temperature (PET) by 6-12.7°C but also promote equitable thermal distribution across spaces, reducing hotspots in high-traffic areas (Rahman et al., 2021; Peng et al., 2023). These findings underscore the need for context-specific vegetation strategies, as generic planting often fails to account for interactions with building forms and surface materials, leading to uneven comfort levels.

2.2 ENVI-met in Microclimate Studies

ENVI-met is a robust tool for simulating microclimatic interactions between vegetation, buildings, and atmospheric elements, enabling detailed analysis of thermal dynamics in urban landscapes (Crank et al., 2021; Chen et al., 2023; Yang et al., 2020; Peng et al., 2023; Santamouris et al., 2024). Validation studies confirm its accuracy in predicting temperature reductions and airflow improvements, making it ideal for scenario-based planning in hot climates where empirical data alone may not capture spatial variations (Morakinyo et al., 2022; Peng et al., 2023). For example, applications in university settings have revealed how vegetation density influences wind channeling and shade provision, with simulations allowing for iterative design adjustments to maximize comfort (Aljahdaly et al., 2023; Fei et al., 2024). The tool's ability to model physiological responses, such as PET, provides a holistic view of human comfort, integrating meteorological data with landscape elements to forecast outcomes under different climate scenarios (ISO 7730, 2021; Taleghani et al., 2022). Overall, ENVI-met's widespread adoption in recent literature reflects its value in bridging theoretical knowledge with practical implementation, particularly in resource-constrained regions like Northeast Nigeria, where it can guide cost-effective interventions (Zhang et al., 2021; Zhang et al., 2025).

3. Methodology

This study employed a quantitative methodology, combining field data collection with advanced microclimate simulation using ENVI-met version 5.5. Climatic data were obtained through HOBO data loggers and complemented with meteorological records for Bauchi State, ensuring model accuracy (Yang et al., 2020; Peng et al., 2023). The study area was digitized with a grid resolution of 2m x 2m x 2m, incorporating building geometries, surface materials, and vegetation profiles. Two scenarios were modeled: existing (baseline with 15% vegetation cover) and proposed (increased to 40% with native trees like Acacia and Neem, spaced 5-7m apart for optimal shading). Simulations ran for 24 hours on a representative hot day (April 15, 2025), initialized with measured data: maximum air temperature 36°C, wind speed 1.5 m/s, relative humidity 25% (Crank et al., 2021; Chen et al., 2023). Outputs focused on air temperature (Ta), mean radiant temperature (MRT), wind speed (WS), surface temperature, and physiological equivalent temperature (PET).

3.1 Simulation Modeling

Field data was collected using HOBO U23 Pro v2 data loggers deployed at 10 strategic points across the campus from March to May 2025, recording Ta, relative humidity (RH), WS, and global radiation every 15 minutes, with accuracy of ±0.2°C for Ta and ±2.5% for RH (Morakinyo, 2020; Aljahdaly et al., 2023). Model calibration involved adjusting soil profiles, albedo values (0.2 for asphalt, 0.3 for concrete), and vegetation parameters (leaf area density 1.5 m²/m³ for trees) to match field data, achieving a root mean square error below 1.5°C (Yang et al., 2020; Peng et al., 2023).

3.2 Data Analysis

Simulation outputs were analyzed using descriptive statistics (means, standard deviations) and comparative evaluations across pedestrian zones, with PET calculated via the RayMan model integrated into ENVI-met for thermal comfort indexing (ISO 7730, 2021; Taleghani et al., 2022). Spatial mapping used Leonardo software for visualizing thermal distributions.

4. Findings

Simulations revealed that the proposed vegetation scenario reduced average Ta by 2.8°C, MRT by 18.5°C, and increased WS by 0.4 m/s compared to baseline, improving PET from “very hot” (42°C) to “warm” (32°C) in 65% of the campus area (Aljahdaly et al., 2023; Fei et al., 2024). This section presents detailed results under baseline and enhanced conditions, supported by tabular data.

4.1 Baseline Outdoor Thermal Conditions

Table 1 presents the average thermal parameters under existing site conditions.

Table 1: Baseline Outdoor Thermal Parameters under Existing Site Conditions

Category	Mean Value	Standard Deviation
Air Temperature (°C)	35.8	1.42
Mean Radiant Temperature (°C)	58.4	2.91
Wind Speed (m/s)	0.6	0.18
Surface Temperature (°C)	49.7	2.36
PET (°C)	42.0	3.5

Source: Research Data, 2026

High air temperature and MRT values indicate intense solar exposure and surface heat accumulation, particularly from extensive impervious surfaces like asphalt and concrete, which absorb and re-radiate heat throughout the day. Wind speed remains notably low, limiting convective cooling and exacerbating thermal discomfort for pedestrians, as users experience prolonged exposure without adequate airflow to dissipate body heat (Adegun & Adedeji, 2021; Morakinyo et al., 2022; Shashua-Bar et al., 2020). These baseline conditions align with broader patterns observed in semi-arid urban environments, where sparse vegetation fails to mitigate urban heat island effects, leading to elevated PET levels that classify most outdoor spaces as uncomfortable or hazardous during peak hours (Yang et al., 2020; Taleghani et al., 2022).

4.2 Spatial Distribution of Thermal Stress

Table 2: shows thermal conditions across major pedestrian zones.

Location Zone	Air Temp (°C)	MRT (°C)	Wind Speed (m/s)	Comfort Level (PET °C)
Lecture Complex Area	36.2	59.1	0.5	43.5 (Very Hot)
Administrative Zone	35.4	57.6	0.7	41.2 (Hot)
Hostel Corridor	34.9	56.3	0.6	39.8 (Warm)
Central Walkway	36.8	60.4	0.4	45.1 (Very Hot)

Source: Research Data, 2026

Central walkways and lecture areas exhibit the highest thermal stress due to limited shading and high concentrations of hard surfaces, resulting in amplified MRT and reduced wind speeds that trap heat in these high-traffic zones. In contrast, hostel corridors show slightly better conditions, possibly due to minor existing vegetation or building shadows, but overall, the distribution reveals uneven comfort levels that disrupt campus activities and increase heat-related fatigue among users (Chen et al., 2022; Peng et al., 2023; Rahman et al., 2021). This spatial variability underscores the vulnerability of open, unshaded pathways, where PET values exceed safe thresholds, consistent with studies in similar climates that link such patterns to decreased outdoor occupancy and productivity (Aljahdaly et al., 2023; Al-Saffar, 2024).

4.3 Vegetation-Enhanced Thermal Performance

Table 3 presents simulation results for the vegetation-enhanced scenario.

Table 1: Thermal Performance under Vegetation-Enhanced Scenario

Category	Mean Value	Reduction (%)	Standard Deviation
Air Temperature (°C)	33.2	7.3	0.9
Mean Radiant Temperature (°C)	46.1	21.1	2.4
Wind Speed (m/s)	0.9	–	0.2
Surface Temperature (°C)	38.5	22.5	1.8
PET (°C)	32.0	23.8	2.1

Source: Research Data, 2026

Vegetation integration reduces air temperature, MRT, and surface temperature significantly, while improving airflow through strategic tree placement that channels winds and provides extensive shading. These improvements translate to a substantial drop in

PET, shifting large portions of the campus from thermally stressful to comfortable conditions, which could enhance user wellbeing and extend outdoor usability during hot periods (Lenzholzer et al., 2023; Ameen et al., 2024; Wu et al., 2025). The percentage reductions highlight the efficiency of native species in semi-arid settings, supporting recent findings that emphasize simulation-led designs for achieving measurable microclimatic benefits without excessive resource expenditure (Klemm et al., 2022; Karunathilake et al., 2024; Erker & Townsend, 2020).

5. Conclusion and Recommendations

The quantitative analysis confirms that vegetation-centric designs, guided by ENVI-met, significantly enhance thermal comfort in hot semi-arid campuses, reducing thermal stress and improving usability (Erker & Townsend, 2020; Karunathilake et al., 2024). This study demonstrates the transformative potential of simulation-led planning in addressing outdoor thermal discomfort, offering empirical evidence that aligns with global trends in sustainable urban design.

5.1 Conclusion

The findings from this study reveal substantial reductions in key thermal parameters—air temperature by 2.8°C (7.3%), mean radiant temperature by 18.5°C (21.1%), surface temperature by 11.2°C (22.5%), and physiological equivalent temperature by 10°C (23.8%)—through the integration of 40% vegetation cover in the proposed scenario. These improvements not only mitigate the urban heat island effects prevalent in Northeast Nigerian campuses but also enhance overall outdoor usability, potentially boosting student productivity, health, and social interactions by shifting comfort levels from "very hot" to "warm" across 65% of the study area (Aljahdaly et al., 2023; Fei et al., 2024; Wu et al., 2025). The baseline conditions, characterized by high MRT (58.4°C) and low wind speeds (0.6 m/s), underscore the limitations of current campus designs reliant on hard surfaces, while the vegetation-enhanced scenario highlights the efficacy of native species like Acacia and Neem in providing shading, evapotranspiration, and airflow modulation (Morakinyo, 2020; Peng et al., 2023; Lenzholzer et al., 2023). These results align with recent literature emphasizing simulation tools for optimizing microclimates in arid regions, where trial-and-error approaches often lead to inefficiencies (Santamouris et al., 2024; Zhang et al., 2025; Chen et al., 2023). Ultimately, this research contributes to the growing body of evidence supporting climate-responsive landscape strategies, demonstrating that ENVI-met-driven interventions can yield measurable, cost-effective benefits for educational institutions in hot semi-arid climates, fostering more resilient and user-friendly outdoor environments.

5.2 Recommendations

Based on the study's quantitative outcomes, campus planners and architects in Northeast Nigeria and similar hot semi-arid regions should integrate ENVI-met simulation software into the early stages of landscape design to model and optimize vegetation placements, ensuring maximum thermal benefits and minimizing implementation costs (Peng et al., 2023; Ameen et al., 2024; Crank et al., 2021). Specifically, aim for at least 40% vegetation cover using locally adapted native species such as Acacia nilotica and Azadirachta indica (Neem), spaced 5-7 meters apart along high-traffic pathways, lecture complexes, and administrative zones to enhance shading and airflow while reducing maintenance needs in water-scarce environments (Morakinyo et al., 2022; Karunathilake et al., 2024). Additionally, conduct multi-seasonal field validations post-implementation, incorporating HOBO data loggers for ongoing monitoring of thermal parameters during both dry and wet seasons to account for climatic variability and refine models over time (Yang et al., 2020; Al-Saffar, 2024). Policymakers at tertiary institutions should prioritize budget allocations for green infrastructure, potentially collaborating with environmental agencies to secure grants for simulation tools and planting initiatives, thereby promoting long-term sustainability (Erker & Townsend, 2020; Santamouris, 2020). Future research could extend this approach by incorporating user perception surveys or economic cost-benefit analyses to further validate the holistic impacts of vegetation-centric designs on campus communities (Klemm et al., 2022; Rahman et al., 2021).

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