

FIELD-VALIDATED PARAMETRIC ANALYSIS OF OUTDOOR THERMAL COMFORT IN PARKING ENVIRONMENTS IN TIRUCHIRAPPALLI, INDIA

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ANÁLISIS PARAMÉTRICO VALIDADO MEDIANTE MEDICIONES EN TERRENO DEL CONFORT TÉRMICO EXTERIOR EN ESTACIONAMIENTOS EN TIRUCHIRAPPALLI, INDIA

ANÁLISE PARAMÉTRICA VALIDADA EM CAMPO DO CONFORTO TÉRMICO EXTERNO EM AMBIENTES DE ESTACIONAMENTO EM TIRUCHIRAPPALLI, ÍNDIA

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ABSTRACT

Rapid urbanization in warm-humid cities has intensified thermal stress in impervious parking environments. This study evaluates the combined influence of surface albedo, roof Solar Reflectance Index (SRI), vegetation cover, and orientation on outdoor thermal comfort in Tiruchirappalli, India, using field measurements and microclimate simulations. Field measurements from three parking typologies were used to validate ENVI-met simulations ($R^2 = 0.931$ for MRT). A parametric matrix generated thirty-two design iterations across four orientations. Results indicate that mean radiant temperature is the dominant driver of thermal discomfort. Increasing surface albedo and roof SRI alone did not consistently reduce UTCI due to reflected radiation effects. In contrast, 60% vegetation cover significantly reduced peak thermal stress across all orientations. East-West alignment intensified afternoon heat accumulation, whereas Northwest-Southeast orientation moderated peak stress. The optimal configuration of albedo 0.2, SRI 30, and 60% vegetation under NW-SE orientation produced the lowest mean UTCI (32.49 °C).

Keywords

outdoor thermal comfort, universal thermal climate index (UTCI), surface albedo

RESUMEN

La rápida urbanización en ciudades de clima cálido-húmedo ha intensificado el estrés térmico en los estacionamientos con superficies impermeables. Este estudio evalúa la influencia combinada del albedo superficial, del Índice de Reflectancia Solar (SRI, por su sigla en inglés) de la cubierta, de la cobertura vegetal y de la orientación sobre el confort térmico exterior en Tiruchirappalli, India, mediante mediciones en terreno y simulaciones microclimáticas. Este tipo de mediciones, realizadas en tres tipologías de estacionamiento, se utilizaron para validar simulaciones con ENVI-met ($R^2 = 0.931$ para MRT). Una matriz paramétrica generó treinta y dos iteraciones de diseño en cuatro orientaciones. Los resultados indican que la temperatura radiante media es el principal factor del discomfort térmico. El aumento del albedo superficial y del SRI de la cubierta no redujo de forma consistente el UTCI debido a los efectos de la radiación reflejada. En contraste, una cobertura vegetal del 60 % redujo significativamente el estrés térmico máximo en todas las orientaciones. La orientación este-oeste intensificó la acumulación de calor por la tarde, mientras que la orientación noroeste-sudeste moderó el estrés térmico máximo. La configuración óptima del albedo de 0,2, SRI de 30 y vegetación al 60% en la orientación noroeste-sureste produjo el UTCI medio más bajo (32,49 °C).

Palabras clave

confort térmico exterior, índice universal de clima térmico (UTCI), albedo superficial

RESUMO

A rápida urbanização em cidades de clima quente e úmido tem intensificado o estresse térmico em ambientes de estacionamento impermeáveis. Este estudo avalia a influência combinada do albedo de superfície, do Índice de Refletância Solar (SRI, do inglês Solar Reflectance Index) da cobertura, da cobertura vegetal e da orientação sobre o conforto térmico externo em Tiruchirappalli, Índia, por meio de medições em campo e simulações microclimáticas. Medições de campo em três tipologias de estacionamento foram utilizadas para validar as simulações no ENVI-met ($R^2 = 0,931$ para a TRM). Uma matriz paramétrica gerou trinta e duas iterações de projeto distribuídas em quatro orientações. Os resultados indicam que a temperatura radiante média é o principal fator determinante do desconforto térmico. O aumento isolado do albedo de superfície e do SRI da cobertura não reduziu de forma consistente o UTCI, devido aos efeitos da radiação refletida. Em contrapartida, uma cobertura vegetal de 60% reduziu significativamente o pico de estresse térmico em todas as orientações. O alinhamento leste-oeste intensificou o acúmulo de calor no período da tarde, ao passo que a orientação noroeste-sudeste atenuou o pico de estresse. A configuração ideal de albedo de 0,2, SRI de 30 e 60% de cobertura vegetal, com orientação noroeste-sudeste, resultou no menor UTCI médio (32,49 °C).

Palavras-chave

conforto térmico externo, índice climático térmico universal (UTCI), albedo de superfície

INTRODUCTION

Rapid urbanization has intensified the Urban Heat Island (UHI) effect by replacing vegetated land with impervious materials, elevating land surface temperatures (LST) in rapidly growing cities such as Tiruchirappalli (Calhoun et al., 2024; Deepthi et al., 2024). The magnitude of UHI is strongly shaped by urban morphology and surface characteristics, including reflectivity, density, and vegetation distribution (Huang et al., 2025). Among horizontal impervious typologies, parking lots represent a thermally critical yet under-examined infrastructure (Sen, Fernández & Roesler, 2020). The expansion of private vehicle ownership in residential and institutional contexts has substantially increased the extent of paved parking areas, exacerbating localized heat accumulation and outdoor discomfort (Lin, Song & Qin, 2021; Patel & Kaushik, 2023).

Warm-humid climates pose distinct thermal challenges. Elevated humidity constrains evaporative cooling, amplifying physiological stress even under moderate variation in air temperature (T_a). In such environments, mean radiant temperature (MRT) frequently dominates outdoor thermal perception. Open asphalt, concrete, and paver surfaces absorb and store solar radiation, increasing surface temperature and longwave re-radiation (Sen et al., 2020). Low-albedo materials intensify this heat buildup (Ghenai et al., 2023), while limited shading exposes pedestrians to sustained direct solar radiation. Consequently, parking areas often exceed thermal comfort thresholds during peak summer hours.

Material-based mitigation strategies, particularly surface albedo enhancement and reflective roofing, have been widely investigated. Increasing pavement albedo reduces solar absorption (Ghenai et al., 2023), and reflective parking lots have been proposed as microscale UHI mitigation strategies (Sen et al., 2020). However, higher albedo may increase reflected shortwave radiation at the pedestrian level, elevating MRT and offsetting potential comfort gains (Taleghani, 2018; Ghoniem, Fahmy & Kamel, 2025). Similarly, roofing systems with high Solar Reflectance Index (SRI) values reduce surface heating and contribute to broader UHI mitigation (Nutakki et al., 2023; Jandaghian, Lacasse & Guar, 2025). However, in semi-covered parking typologies, reflected radiation may redistribute thermal load rather than eliminate it, particularly in spaces lacking vegetation and effective airflow.

Vegetation consistently demonstrates stronger cooling potential than reflective materials. Converting paved parking areas into tree-covered spaces significantly reduces thermal stress (Parison et al., 2023). Trees lower MRT through shading and evapotranspiration while moderating T_a (Rodriguez et al., 2025; Wei, Cheng & Lin, 2025). Broader urban greening strategies have demonstrated evening cooling and improved thermal

stability (Calhoun et al., 2024), and green infrastructure enhances thermal comfort across climatic contexts (Gidey & Mhangara, 2025; Silva Nascimento et al., 2025). Vegetation structure, including canopy density and configuration, further influences pedestrian comfort outcomes (He & Reith, 2023; Pattnaik, Rahman & Pauleit, 2025). In fact, comparative analyses indicate that tree planting may outperform low-albedo pavements in optimizing summer comfort (Zhang et al., 2025).

Spatial orientation introduces an additional, albeit less integrated, parameter. Urban alignment influences solar interception, shadow dynamics, and airflow distribution (Abdelwahab, Fekry & Hamed, 2025; Huang et al., 2025). Certain orientations prolong afternoon exposure and intensify radiant accumulation, whereas oblique configurations can moderate peak stress (Rachidi et al., 2026). Studies in Indian contexts confirm that orientation significantly affects solar heat gain and microclimatic performance (Kaushik S. & Amraotkar, 2026; Peter & Kaushik, 2024; Pachauri & Kaushik S., 2025). However, the combined effects of orientation, surface reflectivity, and vegetation density across parking typologies remain insufficiently quantified.

Outdoor thermal comfort assessment relies on indices integrating meteorological and radiative parameters. The Universal Thermal Climate Index (UTCI), Physiological Equivalent Temperature (PET), and Heat Index (HI) are widely applied to evaluate pedestrian heat stress (Silva Nascimento et al., 2025; Peter & Kaushik, 2024). Outdoor thermal comfort indices such as UTCI and PET both incorporate MRT and are therefore particularly suitable for evaluating pedestrian thermal conditions in highly radiative outdoor environments. In contrast, HI primarily considers air temperature and relative humidity and does not explicitly account for radiative exchange or wind effects. UTCI was selected in this study due to its extensive application in outdoor urban climate research and its suitability for evaluating dynamic outdoor thermal conditions in warm-humid environments (Wang et al., 2020; Kafy, Alsulamy & Alsaleh, 2026). Since the study was conducted in a tropical warm-humid climate, UTCI values were interpreted using the calibrated hot-humid climate scale proposed in recent literature, where 21.8–30.9 °C corresponds to no thermal stress and 30.9–39.0 °C corresponds to moderate heat stress (Chen, Fang & Hwang, 2025). Recent studies in tropical climates have also combined ENVI-met validation with field measurements and assessments of pedestrian thermal comfort to evaluate the effectiveness of integrated bioclimatic mitigation strategies in outdoor environments (Austin, Solano & Chen Austin, 2025).

Despite extensive research on albedo, cool roofs, vegetation, and orientation independently, integrated, field-validated analyses that combine these parameters in warm-humid parking environments remain limited. Most studies focus on isolated interventions or on hot-

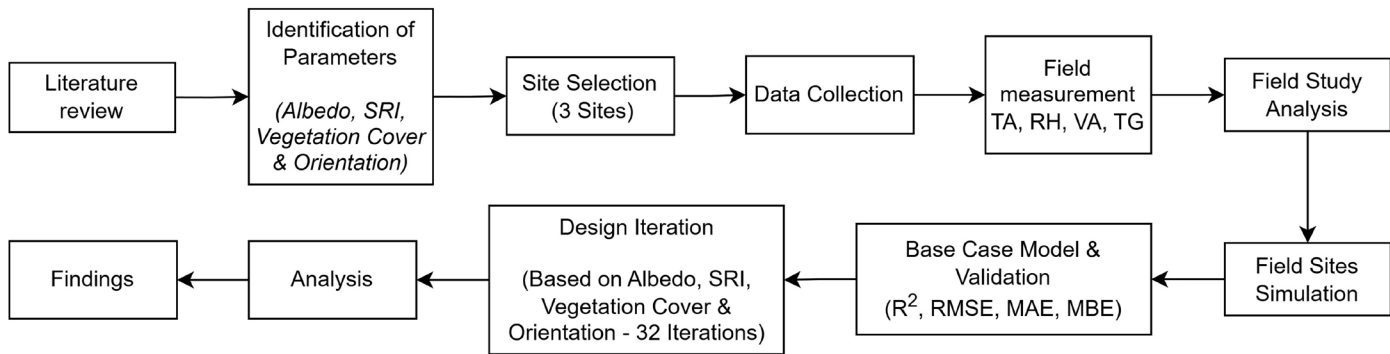


Figure 1. Methodology. Source: Prepared by the authors.

arid and temperate climates, where evaporative and radiative balances differ substantially. This gap restricts the development of climate-responsive design guidelines and may lead to oversimplified reflectivity-based solutions that inadvertently increase pedestrian radiant exposure.

This study addresses this deficiency through a combined field measurement and simulation-based investigation in Tiruchirappalli, India. Three representative parking typologies were instrumented during peak summer conditions, and the data were used to validate ENVI-met simulations (R^2 up to 0.931 for MRT). A structured parametric matrix subsequently evaluated thirty-two design iterations across four orientations, systematically varying surface albedo, roof SRI, and vegetation cover. By integrating radiative management, canopy density, and solar alignment within a validated warm-humid framework, this research advances understanding of pedestrian-level thermal dynamics in parking environments and proposes an orientation-sensitive optimization strategy for climate-responsive tropical design.

Although prior studies have examined vegetation, reflective pavements, cool roofs, and orientation independently, few investigations have quantified their combined interaction within parking environments under warm-humid climatic conditions using field-validated simulations. Existing literature generally evaluates these mitigation measures in isolation, which limits the development of practical design guidance for real urban settings where vegetation may be constrained by space, maintenance, or water availability. This study addresses this gap by identifying how orientation modifies the thermal performance of surface reflectivity and canopy cover, and by establishing a hierarchy of mitigation strategies for parking microclimates.

Accordingly, this study aims not only to quantify the individual and combined influence of surface albedo, roof SRI, vegetation cover, and spatial orientation on pedestrian-level outdoor thermal comfort in parking environments, but also to identify the relative effectiveness and interaction hierarchy of these design

variables under warm-humid climatic conditions. A further aim is to translate the simulation outcomes into a practical decision-support framework for contexts where vegetation is limited or infeasible.

Based on previous urban thermal comfort studies, the research hypothesizes that: (1) vegetation cover exerts a stronger influence on pedestrian thermal comfort than reflective material properties; (2) increasing surface albedo and roof SRI may not proportionally improve UTCI due to enhanced reflected shortwave radiation and elevated MRT; (3) diagonal orientations such as Northwest-Southeast reduce peak thermal stress more effectively than East-West alignment under tropical solar conditions and (4) the thermal effectiveness of reflective mitigation strategies is dependent on orientation and vegetation context, indicating that albedo and roof SRI cannot be evaluated independently of solar geometry and canopy conditions.

METHODOLOGY

This study adopted an integrated empirical computational framework to evaluate outdoor thermal comfort in urban parking environments under warm-humid climatic conditions. The methodological approach combined field-based microclimatic measurements, three-dimensional numerical simulations using ENVI-met v5.7.2, statistical validation of simulated outputs, and systematic parametric evaluation of design variables. The sequential workflow from site characterization to optimization analysis is illustrated in Figure 1.

The study was conducted in Tiruchirappalli (10.79°N), Tamil Nadu, India, a rapidly urbanizing Tier-2 city characterized by high solar radiation intensity, elevated humidity, and persistent summer heat stress (Kaushik S. & Amraotkar, 2026; Pachauri & Kaushik S., 2025). Three representative parking typologies were selected to capture variation in surface materials, roofing conditions, vegetation presence, and spatial orientation. Site 01 (S01) comprises

Site	Orientation	Ground Surface (Albedo)	Roof Condition (SRI)	Vegetation – On Site	Vegetation – Context (N / S / E / W)
S01	330°–150° (N–S)	Driveway: Paver (0.25) Parking: Paver (0.25)	Driveway: Uncovered. Parking: Blue GI sheet (SRI 24)	3 trees; trunk height 4–5 m; sparse canopy	N: 4–5 Neem (Dia 1.5–2.5 m) S: 3 Neem (Dia 2–3 m) + shrubs + grass E: 1 large thick trunk (Dia 2 m) + 1 short dense tree (Dia 4–5 m) W: 2 medium trunk trees (Dia 3–4 m; medium dense)
S02	0°–180° (N–S)	Driveway: Paver (0.25) Parking: PCC (0.30)	Driveway: Uncovered Parking: Green-coated metal sheet (SRI 31)	Nil	N: 1 medium dense (Dia 4–5 m) + 4 small low dense (Dia ~1 m) S: No vegetation E: No vegetation W: 3 medium trunk trees (Dia 2–3 m; medium dense)
S03	0°–180° (N–S)	Driveway: Paver (0.25) Parking: Paver (0.25)	Driveway: Partially tree-shaded Parking: Fully under tree shade	7 Neem trees; low-medium density; long trunk; no shrubs; LAD: 3.5; LAI: 0.4 m ² /m ³	N: 2 Neem (Dia 4–5 m; medium dense; long trunk) + 1-storey building S: 2 Neem (Dia 4–5 m; medium dense) E: 2 Neem (Dia 4–5 m; medium dense) + Bank (1-storey) W: 1 Neem (Dia 4–5 m; medium dense) Note: Trunk angles vary; sparse branching

Table 1. Characteristics of Site 01 (S01), Site 02 (S02) and Site 03 (S03). Source: Prepared by the authors.

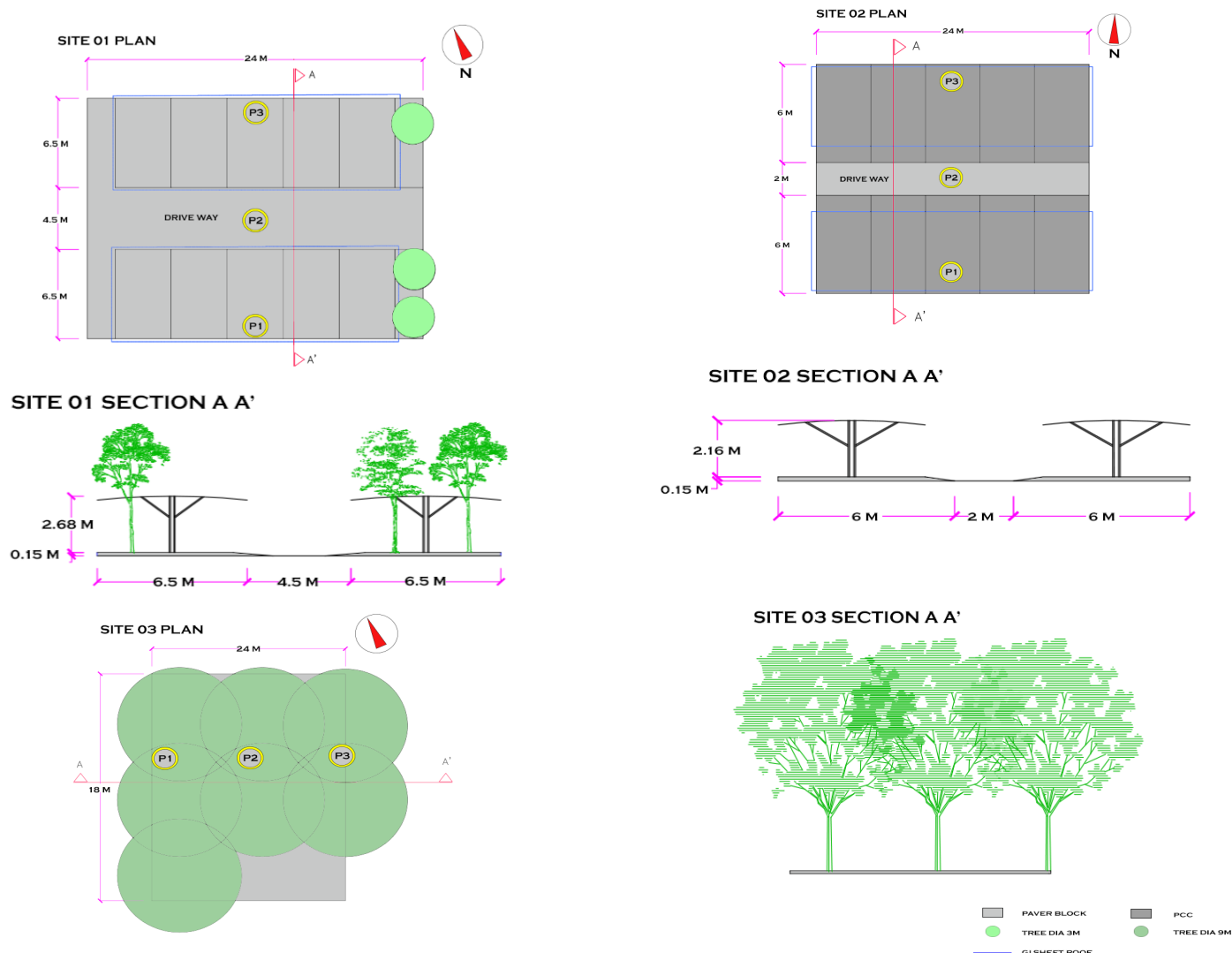


Figure 2. Illustration of the Site 01, Site 02, and Site 03. Source: Prepared by the authors.

Parameters	Units	Instrument	Accuracy	Image
Ta	°C	DeltaOHM_ HD32.3	1/3 DIN	
RH	%		±1.5% (0...90%RH) / ±2% (90...100%RH) @T=15...35°C (1.5 + 1.5% reading) % @ T= remaining range	
Tg	°C		Class 1/3 DIN	
Va	m/s		± 0.2 m/s (0.1÷1 m/s) ± 0.3 m/s (1÷5 m/s)	

Table 2. Parameters and Instruments used for field Measurements. Source: Prepared by the authors.

a semi-covered configuration with blue galvanized metal roofing (SRI 24) and paver block flooring (albedo 0.25). Site 02 (S02) incorporates green-coated metal roofing (SRI 31) with mixed paver and PCC surfaces (albedo 0.25–0.30). Site 03 (S03) represents an open typology, shaded predominantly by mature neem trees (*Azadirachta indica*), with no artificial roofing. Spatial layouts and sectional characteristics are illustrated in Figure 2, while detailed physical attributes are provided in Table 1.

Field measurements were conducted on 28 May 2025, which was identified as the hottest day in the region based on decadal meteorological data. The selected day was characterized by high solar radiation intensity, predominantly clear-sky conditions, and elevated ambient temperatures representative of extreme summer heat exposure in Tiruchirappalli. The measurement campaign was therefore intended to evaluate pedestrian-level thermal stress under peak warm–humid climatic conditions. While the selected extreme-day approach enables assessment of maximum thermal stress conditions relevant to climate-responsive parking design, additional multi-day and multi-season investigations would further improve the generalization to broader climates. Data were recorded during three representative pedestrian exposure periods: morning (MRG), 9:45–10:45; afternoon (AFT), 12:45–13:45; and evening (EVE), 16:45–17:45. At each site, three measurement points were established to represent exposed and shaded/covered zones. All measurements were taken at 1.5 m above ground level to reflect pedestrian thermal exposure. MRT was calculated from globe temperature (T_g) measurements following ISO 7726 procedures for outdoor thermal environments. Measurements were obtained using a standard black globe thermometer with an emissivity of 0.95 and a diameter of 150 mm. The MRT calculation incorporated T_g , air temperature (T_a), and wind speed (V_a) to account for convective heat transfer effects under outdoor conditions (Equation 1). The estimated MRT values are subject to uncertainty associated with measurement variability in globe temperature, air temperature, and wind speed under outdoor field conditions. All instruments were field-checked prior to measurements to ensure operational

consistency under outdoor summer conditions and were compliant with ISO 7726. Measurement specifications, units, and accuracy ranges are summarized in Table 2.

$$MRT = \left((T_g + 273.15)^4 + \left(\frac{1.10 \times 10^8 \times V_a^{0.6}}{\epsilon \times D^{0.4}} \right) \times (T_g - T_a) \right)^{0.25} - 273.15 \quad (\text{Equation 1})$$

Where:

T_g is globe temperature (°C)

T_a is air temperature (°C)

V_a is wind speed (m/s)

ϵ is globe emissivity

D is globe diameter (m).

Microclimatic simulations were performed using ENVI-met v5.7.2, a three-dimensional non-hydrostatic model capable of resolving radiative transfer, airflow dynamics, vegetation processes, and surface–atmosphere interactions at microscale resolution. The computational domain replicated the parking typology with a horizontal extent of 24 m × 22 m. A 2 m × 2 m grid resolution was applied in the horizontal directions, with a base vertical resolution of 0.1 m to capture near-ground gradients relevant to pedestrian comfort. Simulations were conducted for the same time intervals as field observations. Output variables were extracted using the Leonardo post-processing tool.

The ENVI-met simulations were initialized using meteorological conditions corresponding to the field measurement period. Initial atmospheric temperature, relative humidity, and wind conditions were taken from field observations and regional meteorological data for 28 May 2025. Simulations were conducted continuously for 24 hours, from 10 pm on 27 May 2025 to 10 pm on 28 May 2025, to stabilize surface–atmosphere energy exchange processes prior to daytime analysis. Wind speed at a height of 10 m above ground was specified based on measured site conditions, with a prevailing south–southwesterly wind direction. Clear-sky boundary conditions were adopted to represent the extreme summer heat event investigated in this study. Model inputs

Parameter	Specification
Software	ENVI-met v5.7.2
Simulation Date	28 May 2025
Grid Resolution	2 m (X), 2 m (Y), 0.1 m (Z)
Domain Size	24 m × 22 m
Evaluation Metrics	Ta; RH; Va; MRT; UTCI
Vegetation Model	Neem (<i>Azadirachta indica</i>); Height: 9 m; Crown Diameter: 9 m; LAI: 3.5
Design Variables	Albedo: 0.2, 0.4, 0.6 SRI: 30, 60, 90 Vegetation Cover: 0%, 20%, 40%, 60%
Simulation Periods	Morning (09:00–10:00); Afternoon (13:00–14:00); Evening (16:00–17:00)
Iterations	32 simulation scenarios

Table 3. Model Inputs and Assumptions. Source: Prepared by the authors.

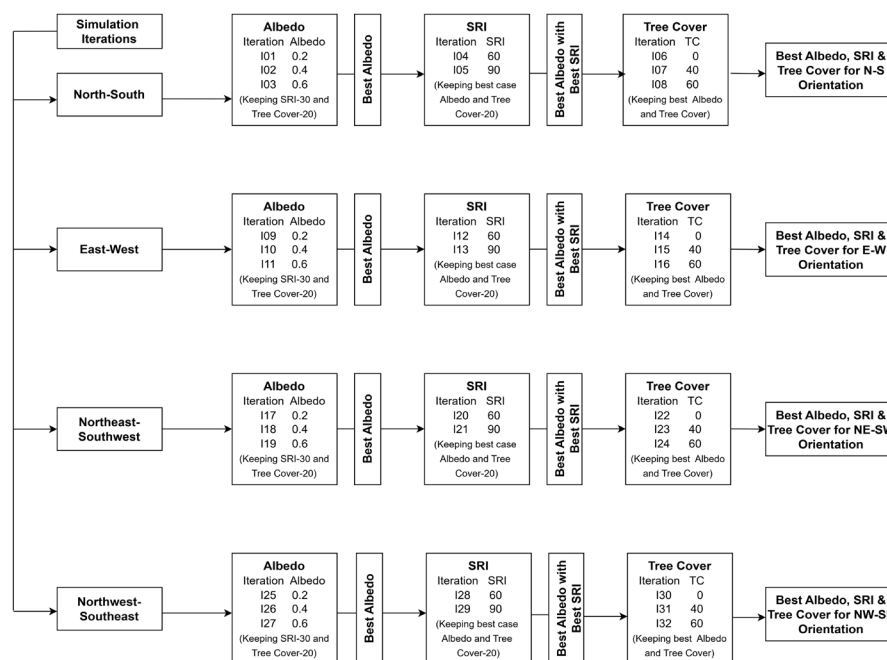


Figure 3. Parametric Design Iterations. Source: Prepared by the authors.

and assumptions are summarized in Table 3. ENVI-met resolves direct, diffuse, and reflected radiative exchange through integrated radiative transfer algorithms. This study focused primarily on the resulting MRT and UTCI responses rather than on the decomposition of individual radiative flux components. The computational domain was developed to represent the immediate parking microclimate and the surrounding contextual elements that influence pedestrian-level thermal conditions. While the selected domain size enabled detailed microscale analysis with manageable computational demand, possible edge effects associated with localized simulation domains are acknowledged as a limitation of the study.

Model validation was conducted by directly comparing

simulated and measured values under identical spatial and temporal conditions. Predictive reliability was evaluated using the coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE), and mean bias error (MBE). These indicators quantify explanatory strength, dispersion accuracy, and systematic deviation. Validation statistics are presented in Table 4. Strong agreement between measured and simulated Ta and MRT confirmed the suitability of the ENVI-met model for subsequent parametric assessment.

Following validation, a structured parametric matrix was developed to evaluate the combined influence of surface albedo, roof SRI, vegetation cover, and spatial orientation. Surface albedo values of 0.2, 0.4, and 0.6 represented

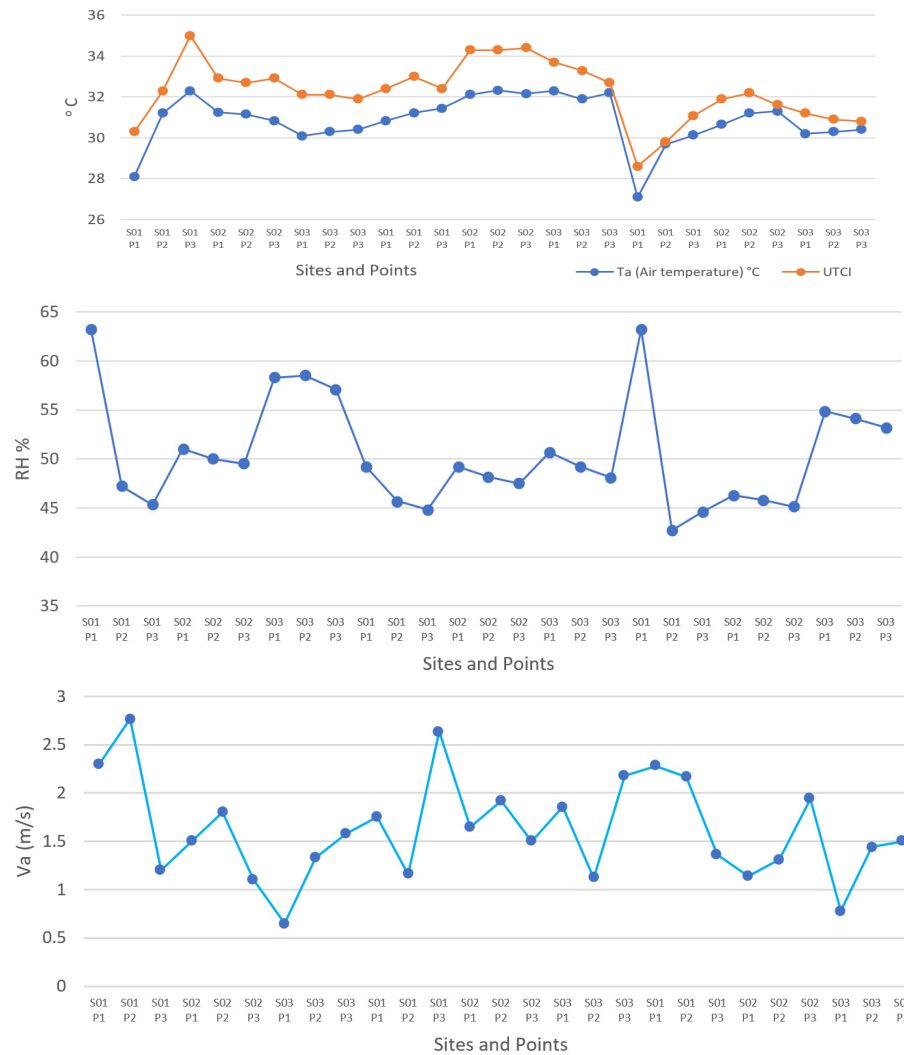


Figure 4. Time series field measurement data of Ta, UTCL, RH, Va for S01, S02, S03. Source: Prepared by the authors.

low-, medium-, and high-reflectivity pavements. Roof SRI values of 30, 60, and 90 simulated varying levels of reflective performance. Vegetation scenarios modeled *Azadirachta indica* with a height of 9 m, a crown diameter of 9 m, and a Leaf Area Index (LAI) of 3.5 to represent mature canopy conditions. Vegetation cover was varied at 0%, 20%, 40%, and 60% along the site perimeter to evaluate the effects of shading and evapotranspiration.

The parametric evaluation followed a stepwise matrix approach. For each orientation, North–South, East–West, Northeast–Southwest, and Northwest–Southeast, a base configuration reflecting prevalent local practice (albedo 0.2, SRI 30, 20% vegetation) was first modeled. Subsequently, albedo was varied while keeping SRI and vegetation constant to determine the optimal surface reflectivity. Using the identified albedo value, the roof SRI was varied, followed by systematic modifications to vegetation cover. This structured approach resulted in eight iterations per orientation, producing a total of

thirty-two simulation scenarios (I01–I32). This matrix-based design enabled the evaluation of both individual parameter effects and their interactions under the different solar alignments (Figure 3). Thermal performance across all scenarios was assessed primarily using the UTCL, with support from analyses of Ta and MRT. The comparative framework allowed identifying optimized configurations to reduce pedestrian-level heat stress in tropical parking environments.

RESULTS AND ANALYSIS

FIELD MEASUREMENT ANALYSIS

Field measurements demonstrated pronounced diurnal variation across the three parking typologies (Figure 4). All sites exhibited progressive thermal escalation from morning to afternoon, with peak stress occurring between

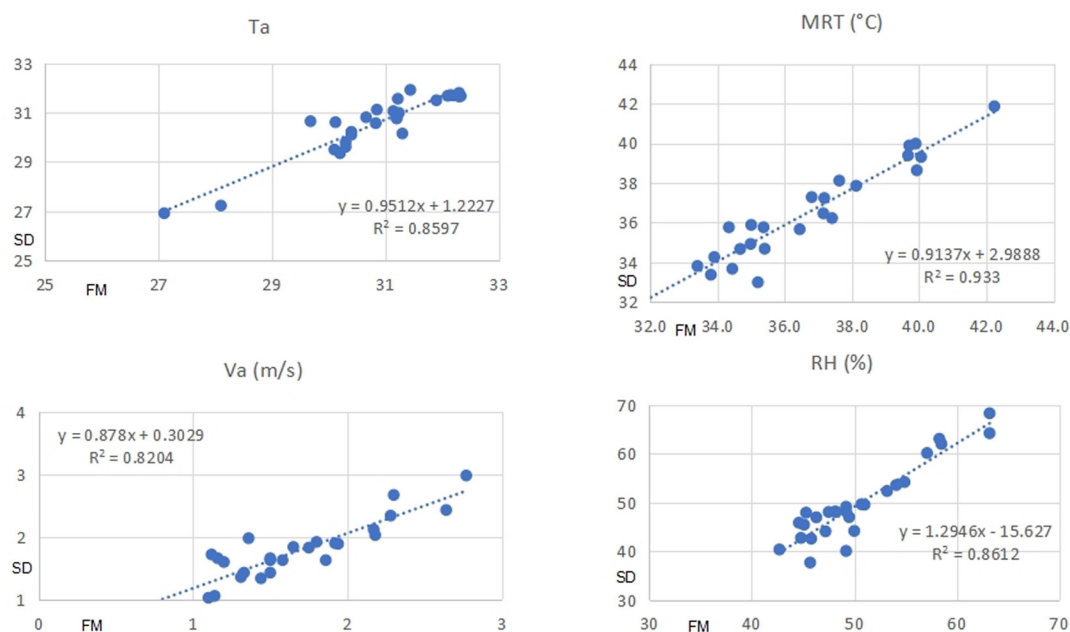


Figure 5. Field Measurement (FM) and Simulation Data (SD) Validation. Source: Prepared by the authors.

Variable	R ²	RMSE	MAE	MBE
Ta	0.795	0.55 °C	0.48 °C	-0.28 °C
RH	0.624	3.37 %	2.42 %	-0.76 %
Va	0.776	0.25 m/s	0.18 m/s	+0.10 m/s
MRT	0.931	0.77 °C	0.59 °C	-0.13 °C

Table 4. Validation Statistics Comparing Field-Measured and Simulation Variables. Source: Prepared by the authors.

12:45 and 1:45 PM, followed by partial evening recovery. However, the magnitude and persistence of thermal stress varied systematically with surface characteristics, roofing configuration, and the presence of vegetation.

Sites S01 and S02, both incorporating metal roofing sheets with low-to-moderate SRI 24 and 31, recorded elevated MRT and UTCI during peak hours. Despite partial shading, afternoon UTCI values exceeded 33–34°C in semi-covered areas and were higher in exposed driveway zones. The combined effect of low-albedo paving and re-radiation from heated metal roofing intensified the radiant load. Wind speeds beneath sheds were comparatively reduced, limiting convective dissipation and further amplifying thermal accumulation.

In contrast, Site S03, fully shaded by a mature neem canopy and lacking artificial roofing, demonstrated consistently lower MRT during peak hours despite comparable air temperature. Vegetation reduced direct solar interception and moderated longwave exchange, resulting in lower UTCI across measurement points.

Moreover, S03 exhibited more rapid evening recovery, indicating reduced thermal storage and enhanced microclimatic stabilization via evapotranspiration. These field observations establish MRT as the dominant differentiator among typologies and provide empirical grounding for subsequent simulation-based analysis.

Correlation Analysis

Pearson correlation analysis confirms the dominant role of radiative exposure. Ta ($r = 0.894$, $p < 0.001$) and MRT ($r = 0.668$, $p < 0.001$) showed strong positive associations with UTCI, whereas wind speed exhibited a weak and statistically insignificant correlation. The findings reinforce the conclusion that in warm-humid parking environments, radiant heat exchange exerts a greater influence on pedestrian stress than convective mechanisms.

MODEL VALIDATION

Model validation was performed by comparing field-measured and ENVI-met simulated parameters under

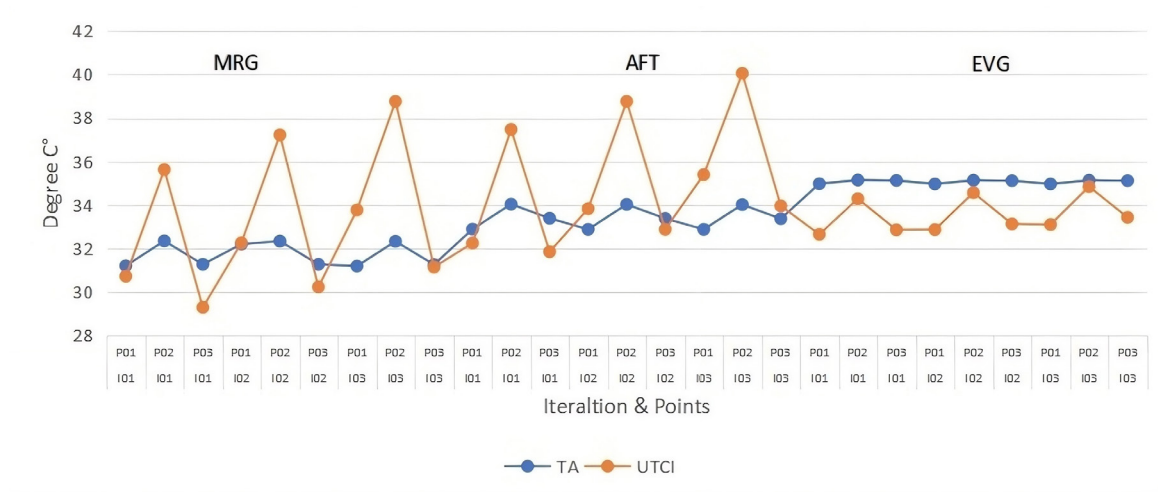


Figure 6. Time series data of Ta & UTCI for I01, I02, I03. Source: Prepared by the authors.

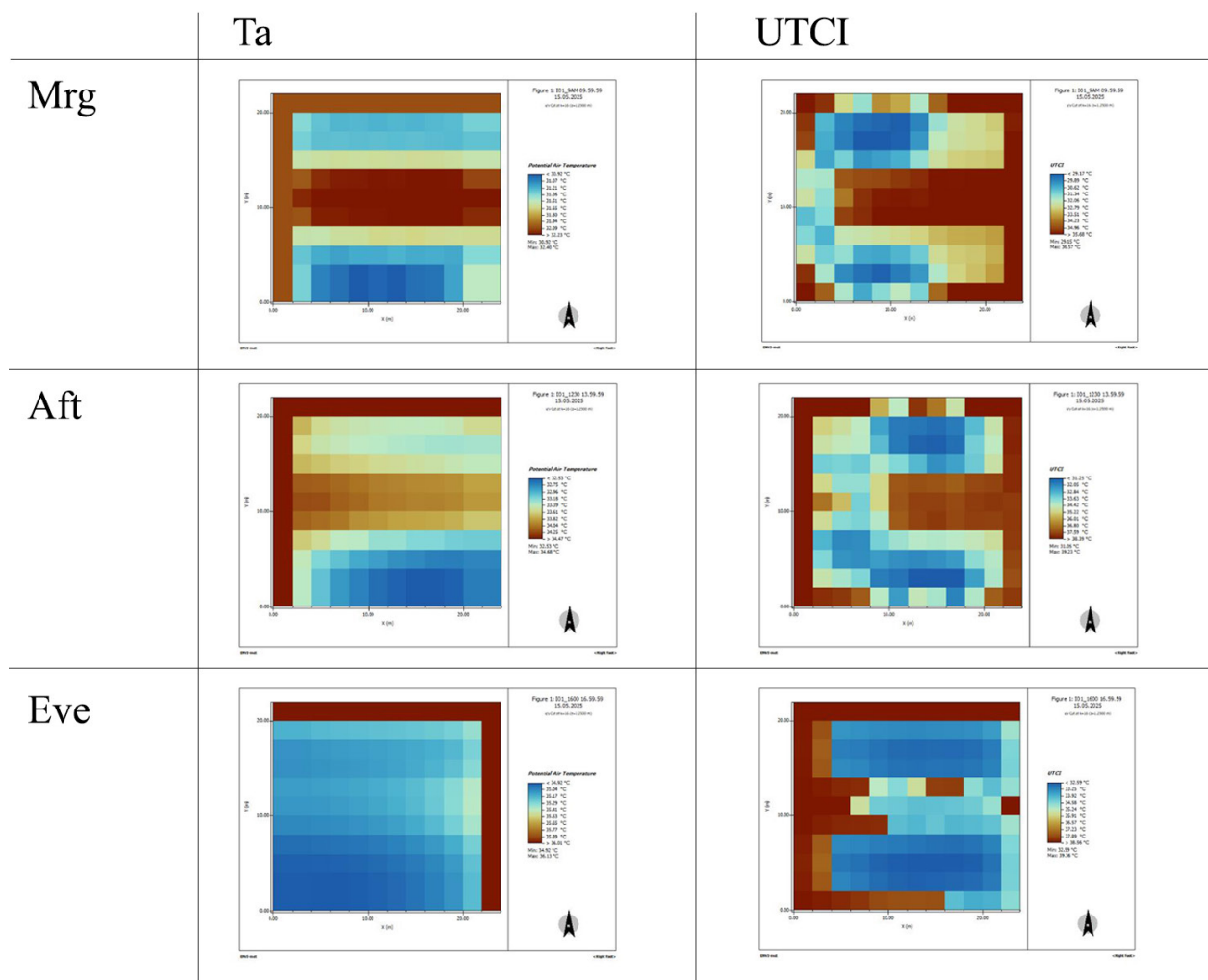


Figure 7. Ta and UTCI Map of I01. Source: Prepared by the authors using Envi met-v5.7.2.

identical temporal and spatial conditions (Figure 5). The validation results demonstrate acceptable agreement ($R^2 = 0.931$; $RMSE = 0.77\text{ }^{\circ}\text{C}$) between measured and simulated thermal parameters under the investigated climatic conditions, indicating that the ENVI-met model is suitable for comparative parametric assessment of parking microclimates (Table 4). T_a also showed robust performance ($R^2 = 0.795$; $RMSE = 0.55\text{ }^{\circ}\text{C}$). Wind speed achieved satisfactory correlation ($R^2 = 0.776$), while relative humidity presented moderate but acceptable agreement ($R^2 = 0.624$). Mean Bias Error values for T_a and MRT remained within $\pm 1\text{ }^{\circ}\text{C}$, indicating minimal systematic deviation. Overall, the validation statistics confirm that the ENVI-met framework reliably captures microclimatic dynamics and is suitable for parametric evaluation of outdoor thermal comfort in parking typologies.

PARAMETRIC SIMULATION RESULTS

North-South Orientation

Under North-South alignment, simulations reveal distinct sensitivity to vegetation density, with comparatively limited responses to variations in albedo and SRI (Figure 6). Across iterations, UTCI peaked at the exposed driveway point (P2), confirming direct solar exposure as the primary stress driver. Evening recovery remained incomplete under low-vegetation scenarios (Figure 7).

Increasing surface albedo from 0.2 to 0.6 did not result in proportional reductions in UTCI. In exposed zones, higher albedo marginally increased peak UTCI, indicating enhanced shortwave reflection and elevated MRT. Similarly, increasing roof SRI from 30 to 90 produced negligible pedestrian-level improvement, suggesting that reflective gains were offset by radiative redistribution.

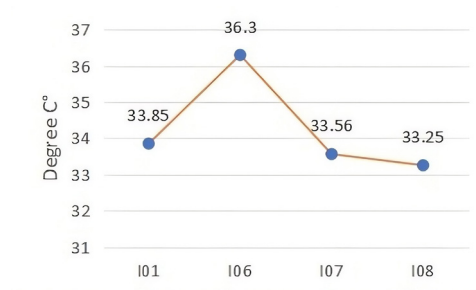


Figure 8. UTCI Average over time for I01, I06, I07, and I08. Source: Prepared by the authors.

In contrast, vegetation exerted substantial mitigation. As shown in Figure 8, increasing canopy cover from 0% to 60% consistently reduced the average UTCI across time periods, with the greatest reduction during the afternoon peak. Shading significantly reduced MRT and limited heat accumulation. Under this orientation, vegetation clearly dominated over material reflectivity as the principal determinant of thermal comfort.

East-West Orientation

The East-West configuration recorded the highest peak UTCI values among orientations (Figure 9). Afternoon escalation was steeper than for the North-South alignment, reflecting prolonged solar exposure along the parking axis. Albedo and SRI adjustments produced minimal mitigation under this configuration. The orientation intensified both direct and reflected radiation, reducing the effectiveness of reflectivity-based strategies. Although vegetation contributed measurable cooling, its impact was moderated by sustained solar incidence during peak hours. East-West alignment, therefore, exhibited the greatest susceptibility to midday thermal accumulation, particularly in exposed zones.

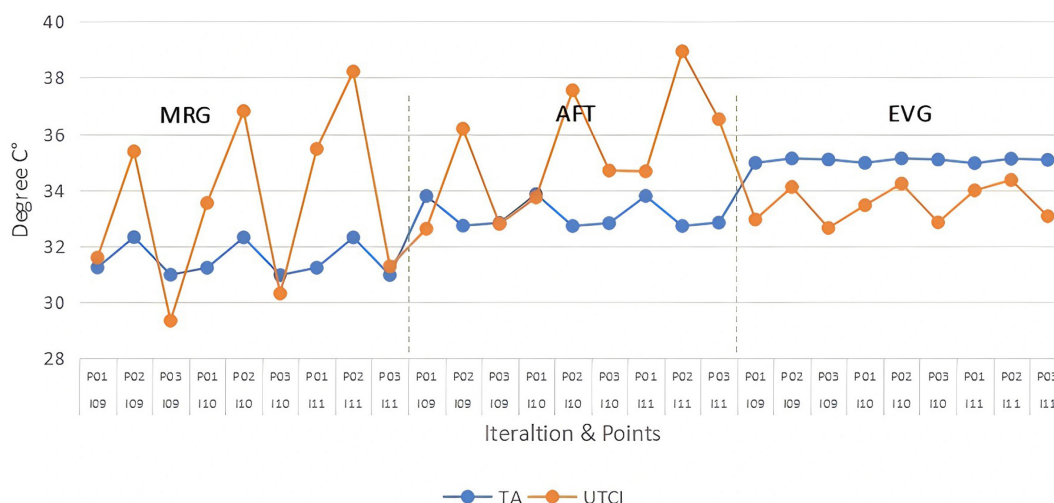


Figure 9. Time-series data for Ta & UTCI for I09, I10, and I11. Source: Prepared by the authors.

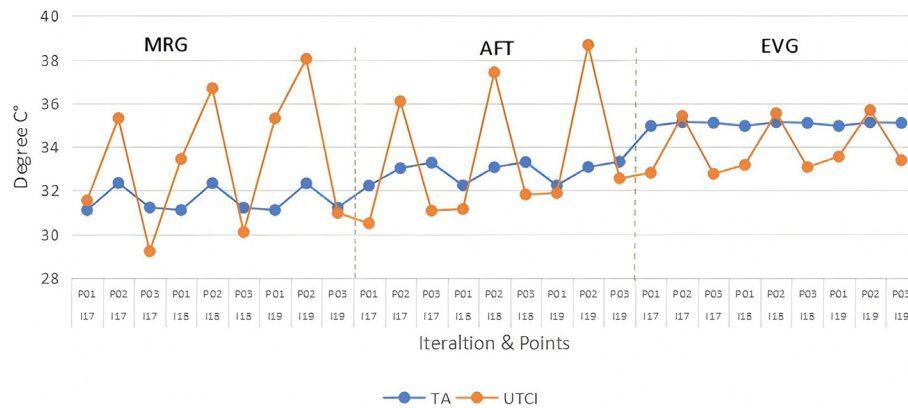


Figure 10. Time-series data for Ta & UTCI for I17, I18, and I19. Source: Prepared by the authors.

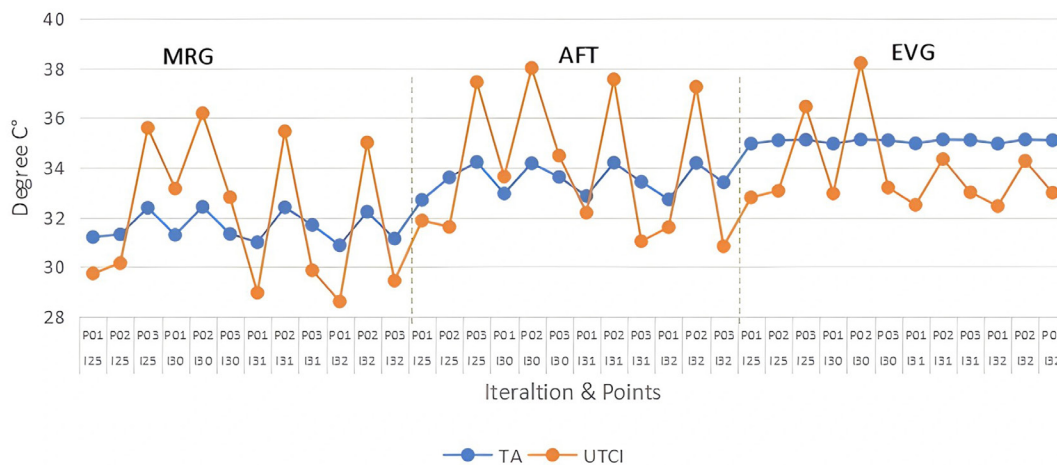


Figure 11. Time-series data for Ta & UTCI for I25, I30, I31, and I32. Source: Prepared by the authors.

Northeast-Southwest Orientation

The Northeast-Southwest (NE-SW) orientation demonstrated moderated diurnal variation relative to East-West alignment (Figure 10). Peak UTCI at P2 remained lower than under the orthogonal East-West configuration, indicating reduced duration of direct solar incidence.

As in other orientations, albedo and SRI adjustments produced limited changes in pedestrian-level UTCI. Vegetation, however, consistently reduced peak values, particularly in semi-exposed zones. The oblique solar alignment reduced radiant accumulation and, when combined with canopy shading, produced more balanced afternoon conditions. This orientation exhibited a moderated peak stress and comparable evening recovery.

Northwest-Southeast Orientation

The Northwest-Southeast (NW-SE) orientation demonstrated the lowest peak UTCI among the tested

alignments (Figure 11). The angular solar trajectory reduced prolonged direct exposure at P2, limiting MRT escalation during peak hours. Material modifications again produced marginal differences. However, vegetation integration resulted in a substantial reduction in the average UTCI (Figure 12). The 60% canopy scenario exhibited the lowest peak stress across all orientations. Shading reduced radiative load and enhanced microclimatic stability in both covered and semi-exposed zones. This orientation, when combined with high vegetation density, exhibited the most favorable thermal performance.

CROSS-ORIENTATION COMPARATIVE ANALYSIS

Comparative analysis reveals systematic differences in peak thermal response (Figure 13). Although the different parking configurations produced measurable reductions in UTCI, most scenarios remained within the calibrated moderate-heat-stress category. Accordingly, the results are interpreted in terms of relative thermal improvement rather than categorical thermal transition. East-West

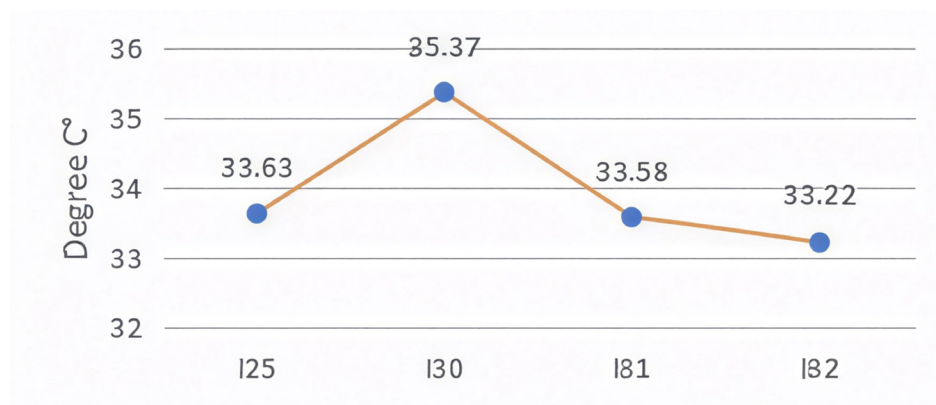


Figure 12. UTCL Average for I25, I30, I81, and I82. Source: Prepared by the authors.

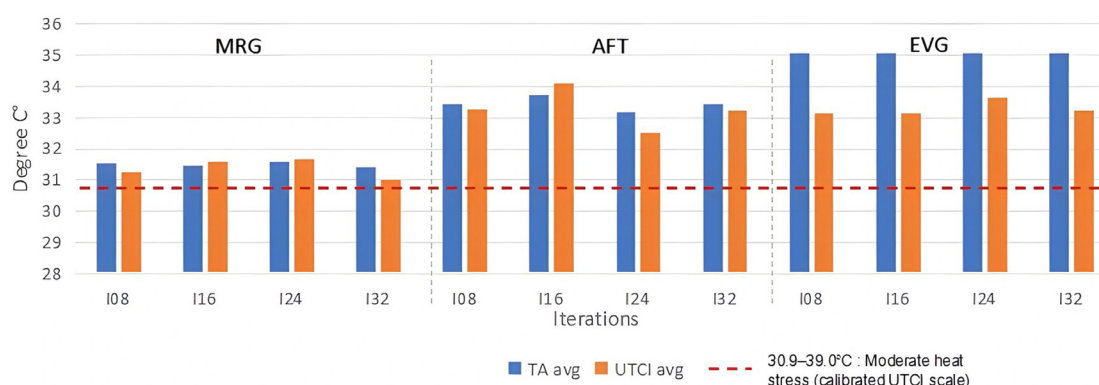


Figure 13. Time series comparison of Ta and UTCL for best-performing iterations (I08, I16, I24, I32). Source: Prepared by the authors.

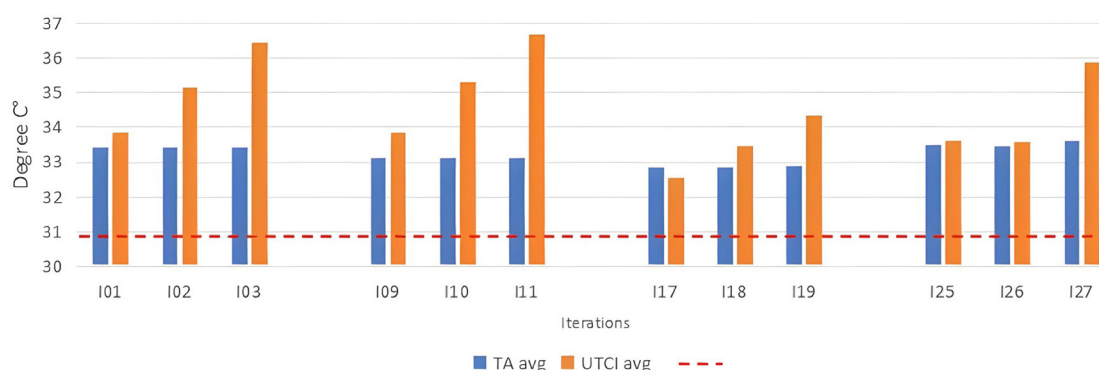


Figure 14. Afternoon comparison of Ta and UTCL across iterations with varying surface albedo values. Source: Prepared by the authors

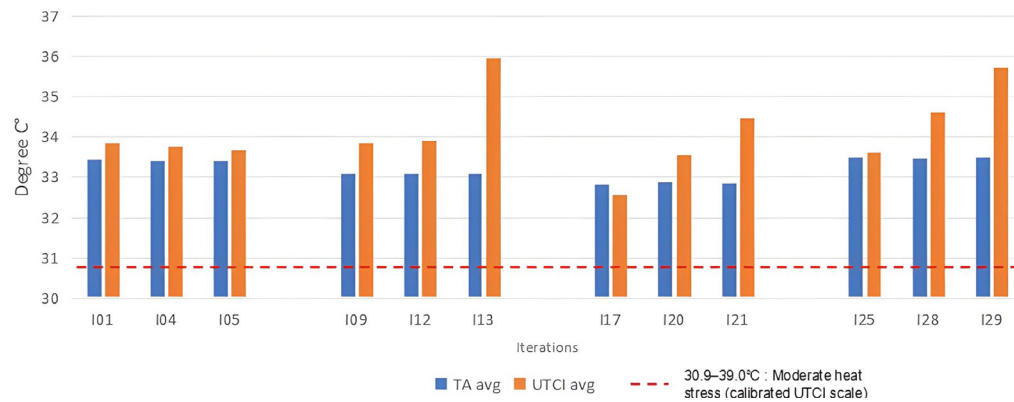


Figure 15. Afternoon comparison of Ta and UTCI across iterations with varying roof SRI values. Source: Prepared by the authors.

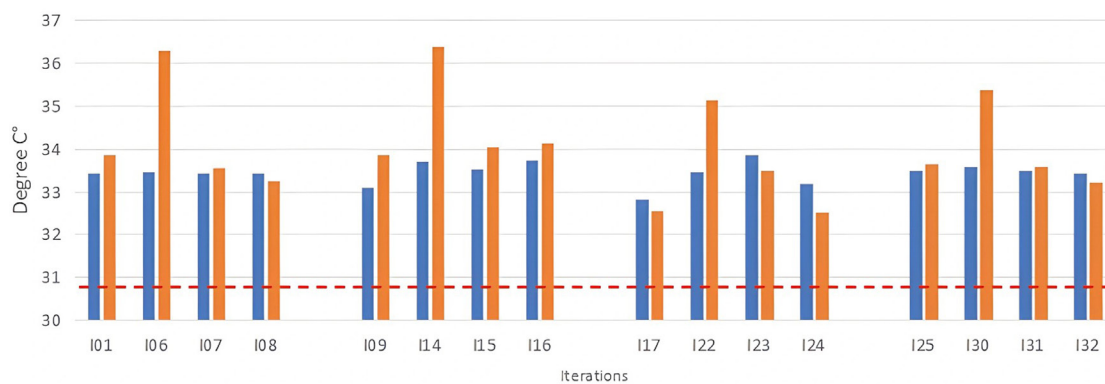


Figure 16. Afternoon comparison of Ta and UTCI across iterations with varying Tree cover. Source: Prepared by the authors.

alignment produced the highest afternoon UTCI, while NW–SE alignment consistently achieved the lowest peak values under equivalent vegetation conditions. North–South and NE–SW orientations exhibited intermediate performance.

Morning conditions were similar across orientations, indicating that alignment primarily influences midday radiative accumulation rather than baseline thermal state. Differences intensified during peak solar intensity, when geometric orientation directly governed duration and angle of incident radiation on exposed surfaces.

Diagonal alignments, particularly NW–SE, reduced peak accumulation more effectively than orthogonal East–West configurations, demonstrating the interaction between solar geometry and surface exposure.

PARAMETER-SPECIFIC EFFECTS

Surface Albedo

Afternoon comparison indicates that increasing albedo from 0.2 to 0.6 did not consistently reduce the UTCI

(Figure 14). In exposed zones, higher reflectivity marginally elevated UTCI due to increased shortwave reflection and MRT. Effects were amplified in orthogonal orientations with sustained solar incidence.

Roof Solar Reflectance Index (SRI)

Increasing SRI from 30 to 90 yielded limited pedestrian-level cooling (Figure 15). Although roof surfaces experienced reduced heating, reflected radiation beneath semi-covered areas redistributed radiant energy toward occupants, constraining overall benefit.

Vegetation Cover

Vegetation demonstrated the strongest mitigation effect (Figure 16). Increasing canopy from 0% to 60% consistently reduced UTCI across orientations, with peak reductions during afternoon stress. Shading significantly lowered MRT and suppressed radiant accumulation, establishing vegetation as the dominant parameter influencing thermal comfort.

Urban condition	Primary design priority	Expected thermal implication
Vegetation feasible	60% canopy cover + NW–SE orientation	Lowest pedestrian thermal stress
Vegetation partially feasible	Moderate canopy + low albedo + moderate SRI	Balanced mitigation with reduced MRT
Vegetation not feasible	Orientation optimization + controlled reflectivity	Orientation becomes the dominant passive strategy
Retrofit context	Shading first, reflectivity second	Avoid reliance on reflective materials alone
Budget-constrained context	Orientation and selective shading	Higher benefit than material-only upgrades

Table 5. Design hierarchy for parking environments under different urban constraints. Source: Prepared by the authors.

Interaction effects between orientation, vegetation, and reflective materials

The results show that the thermal response of surface albedo and roof SRI is not uniform across the study domain but is strongly moderated by orientation and vegetation density. Under low-vegetation conditions, increases in albedo produced limited or adverse UTCI responses because reflected shortwave radiation increased pedestrian-level radiant loading. In contrast, when vegetation cover increased, the negative impact of reflected radiation was reduced due to shading and lower MRT. Orientation also modified the magnitude of these responses: East–West alignment amplified afternoon radiative accumulation, whereas NW–SE alignment moderated peak exposure. These findings indicate that parking thermal performance arises from the interaction among radiative materials, canopy configuration, and solar geometry rather than from any single design variable in isolation.

Table 5 represents a key contribution of this study by translating the field-validated parametric analysis into an operational design hierarchy for parking environments in warm–humid climates. The framework demonstrates that the thermal effectiveness of mitigation strategies is not universal but strongly depends on the interaction of vegetation availability, orientation, and reflective surface properties. While vegetation consistently exhibited the greatest reduction in pedestrian heat exposure, the results reveal that orientation becomes the dominant passive design determinant when canopy integration is restricted. Furthermore, the limited and context-dependent benefits of high-albedo pavements and reflective roofing suggest that material-based interventions should be implemented in conjunction with, rather than as substitutes for, spatial and landscape design strategies. Consequently, the proposed framework moves beyond isolated parameter evaluation and provides a decision-support tool that links microclimatic performance with realistic urban design constraints, thereby facilitating more effective climate-responsive planning and retrofit decisions.

STATISTICAL ANALYSIS

Statistical analysis was performed on the complete dataset ($n = 288$) to quantify the relationship between environmental parameters and outdoor thermal comfort. Pearson correlation analysis revealed a strong positive association between MRT and UTCI ($r = 0.653$, $p < 0.001$), confirming the dominant role of radiative heat exchange in influencing pedestrian thermal stress. Ta demonstrated a moderate positive correlation ($r = 0.358$, $p < 0.001$), while relative humidity showed a negative correlation ($r = -0.432$, $p < 0.001$), indicating partial moderation of UTCI under simulated conditions. Wind speed exhibited a weak and statistically insignificant correlation, suggesting limited convective influence within the parking configuration.

A multiple linear regression model was developed to predict UTCI as a function of air temperature, MRT, relative humidity, and wind speed. The regression model demonstrated strong explanatory capability within the investigated dataset ($R^2 = 0.87$, $p < 0.001$) and was used to evaluate the relative influence of environmental variables on UTCI under the investigated climatic conditions. The derived predictive relationship (Equation 2) is expressed as:

$$\text{UTCI} = -2.658 + 0.841(\text{Ta}) + 0.229(\text{MRT}) - 0.003(\text{RH}) - 0.614(\text{Wind})$$

(Equation 2)

Standardized regression coefficients indicate that MRT exerts the strongest influence on UTCI among the evaluated environmental variables, confirming radiative exposure as the dominant contributor to pedestrian thermal stress. The results further indicate that vegetation cover and orientation primarily influence outdoor comfort by modulating MRT and solar exposure. The Variance Inflation Factor ($\text{VIF} < 5$) indicates the absence of multicollinearity. These results reinforce radiative load as the governing mechanism of thermal stress.

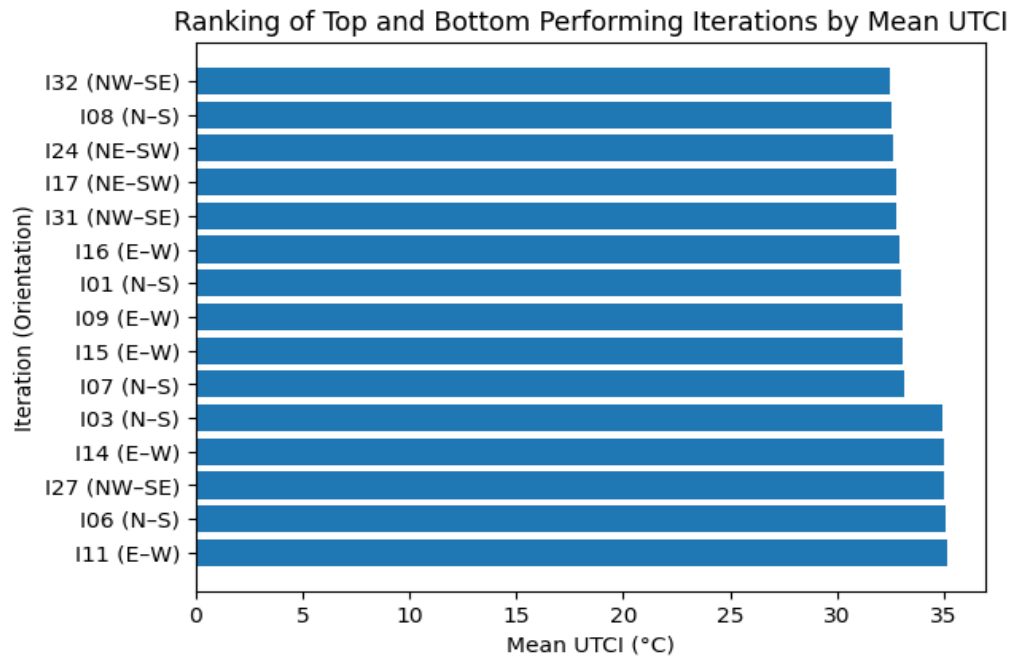


Figure 17. Top and Bottom Performing Iterations Based on Mean UTCI. Source: Prepared by the authors

OPTIMIZATION RANKING

Evaluation of all thirty-two iterations demonstrates clear performance stratification (Figure 17). High vegetation density consistently aligned with lower mean UTCI across orientations. Iteration I32 (NW-SE; albedo 0.2; SRI 30; 60% vegetation) achieved the lowest mean UTCI (32.49°C), reflecting the synergistic interaction between canopy shading and favorable solar alignment. Conversely, minimal vegetation under the East-West alignment (I11) recorded the highest mean UTCI (35.16°C). The ranking pattern unequivocally identifies vegetation integration and orientation as dominant determinants of thermal performance, whereas reflectivity adjustments alone produced limited improvement.

DISCUSSION

The findings confirm that MRT is the dominant driver of outdoor thermal comfort in parking environments, consistent with studies emphasizing the primacy of radiative exchange in pedestrian heat stress (Taleghani, 2018). Increasing surface albedo did not consistently improve comfort, as higher reflectivity elevated pedestrian-level radiant exposure, a phenomenon previously reported where albedo increases from 0.2 to 0.6 raised MRT and thermal stress indices (Ghoniem et al., 2025). Although reflective pavements reduce surface temperatures, their effectiveness depends on shading and spatial context (Taleghani, 2018).

Similarly, higher roof SRI values produced limited pedestrian-scale cooling. While cool materials can reduce surface temperatures and mitigate the UHI (Jandaghian et al., 2025), their impact on comfort is contingent upon surrounding geometry and exposure conditions. In semi-covered parking typologies, reflected radiation may redistribute rather than eliminate thermal load.

Vegetation demonstrated the most substantial cooling effect, corroborating evidence that tree shading reduces thermal stress more effectively than albedo modification (Zhang et al., 2025). The observed reductions under increased canopy cover align with documented cooling through shading and evapotranspiration (He & Reith, 2023). The influence of vegetation density and structure on pedestrian comfort further supports these findings (Pattnaik et al., 2025).

Orientation shaped the magnitude and timing of thermal stress, with East-West alignment intensifying afternoon exposure, consistent with research linking urban morphology and solar penetration to pedestrian comfort (Rachidi et al., 2026). Integrated strategies that combine vegetation, reflective materials, and orientation-sensitive planning therefore offer the most effective pathway to improving thermal comfort in warm-humid parking environments.

Using the calibrated UTCI scale, the investigated parking environments predominantly exhibited moderate heat stress conditions. Within this range, increased vegetation cover and favorable orientation reduced pedestrian thermal exposure more effectively than modifications to

reflective materials alone, by limiting direct solar exposure and lowering MRT. Regression analysis and parametric comparisons further indicate that the thermal influence of albedo, roof reflectivity, vegetation, and orientation is strongly interconnected through their collective impact on pedestrian radiative conditions.

Beyond reaffirming the cooling benefits of vegetation, this study reveals that the thermal effectiveness of reflective materials is highly dependent on orientation and canopy context. While higher albedo and roof SRI reduced surface heat absorption, they did not consistently improve pedestrian thermal comfort due to increased radiative exposure. Under vegetation-constrained conditions, orientation emerged as a more influential determinant of thermal comfort than material reflectivity. These findings underscore the need for integrated mitigation strategies and establish a hierarchy of design interventions for parking environments in warm-humid climates.

STUDY LIMITATIONS AND FUTURE RESEARCH

This study was designed to evaluate the thermal performance of parking under representative peak summer conditions in a warm-humid climate. Consequently, the model validation focused on an extreme summer day and may not fully capture seasonal variability. In addition, MRT was estimated using the ISO 7726 globe-temperature formulation, and thermal comfort was assessed using UTCI as the primary evaluation index. While these methodological choices do not affect the comparative assessment of the investigated design scenarios, future studies should incorporate multi-season observations, uncertainty analysis of derived thermal parameters, alternative comfort indices, and occupant-based thermal perception surveys to further enhance the generalizability of the findings.

CONCLUSION

This study investigated the combined influence of surface albedo, roof SRI, vegetation cover, and orientation on pedestrian-level thermal comfort in warm-humid parking environments. Through field measurements and validated ENVI-met simulations, the results demonstrate that MRT is the dominant determinant of outdoor thermal stress, outweighing isolated modifications in air temperature.

Reflectivity-based strategies alone proved insufficient. Increasing surface albedo and roof SRI reduced material heat absorption but did not consistently lower UTCI due to reflected radiation and radiative redistribution effects. In contrast, vegetation emerged as the most effective mitigation strategy. Increasing canopy cover to 60% consistently reduced peak thermal stress across orientations by lowering MRT through shading and evapotranspiration.

Orientation further mediated thermal accumulation: East-West alignment intensified afternoon exposure, whereas Northwest-Southeast configuration moderated peak stress. The optimal performance was achieved through the combined integration of low albedo (0.2), moderate SRI (30), 60% vegetation cover, and diagonal alignment. These findings underscore that climate-responsive parking design in tropical cities must prioritize radiative management through canopy integration and orientation-sensitive planning rather than reliance on reflective materials alone. While the findings provide important insights into thermal comfort under peak summer conditions, future studies incorporating extended monitoring periods and occupant-based thermal perception assessments would further strengthen the generalization to broader climatic conditions.

Beyond confirming the thermal benefits of vegetation, this study establishes a field-validated hierarchy of mitigation strategies for parking environments in warm-humid climates. The results demonstrate that the thermal effectiveness of reflective materials is not universal but depends on orientation and vegetation context. This provides a decision-support framework for climate-responsive parking design, particularly in urban settings where extensive vegetation cannot be introduced.

AUTHOR CONTRIBUTION CRediT

Conceptualization: A.S.K.S., P.G.; Data Curation: A.S.K.S.; Formal Analysis: A.S.K.S., P.G.; Funding Acquisition: P.G., G.S.; Investigation: A.S.K.S.; Methodology: A.S.K.S., P.G.; Project Administration: P.G., G.S.; Resources: P.G., G.S.; Software: A.S.K.S.; Supervision: P.G., G.S.; Validation: A.S.K.S., P.G., G.S.; Visualization: A.S.K.S.; Writing – Original Draft: A.S.K.S.; Writing – Review & Editing: P.G., G.S.; Writing – Revision & Editing: ASKS, P.G., G.S.

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BIBLIOGRAPHIC REFERENCES

- Abdelwahab, R. A., Fekry, A. A., & Hamed, R.E.-D. (2025). The effective landscape design parameters with high reflective hardscapes: guidelines for optimizing human thermal comfort in outdoor spaces by design -a case on hot arid climate weather. *Computational Urban Science*, 5,28. <https://doi.org/10.1007/s43762-025-00186-w>
- Austin, D., Solano, T., & Chen Austin, M. (2025). Synergistic Effects of Bioclimatic Strategies on Microclimate Improvement: A Numerical-

- Experimental Study at University Campus Scale. *Sustainability*, 17(19), 8867. <https://doi.org/10.3390/su17198867>
- Calhoun, Z.D., Willard, F., Ge, C., Rodriguez, C., Bergin, M., & Carlson, D. (2024). Estimating the effects of vegetation and increased albedo on the urban heat island effect with spatial causal inference. *Scientific Reports*, 14, 540. <https://doi.org/10.1038/s41598-023-50981-w>
- Chen, W.-A., Fang, P.-L., & Hwang, R.-L. (2025). Calibrating the UTCI scale for hot and humid climates through comprehensive year-round field surveys to improve the adaptability. *Urban Climate*, 59, 102267. <https://doi.org/10.1016/j.uclim.2024.102267>
- Deepthi, S., Sudalaimani, K., Radhakrishnan, S. P., & Radhakrishnan, S. (2024). Evaluating urban heat island to achieve sustainable development goals: A case study of Tiruchirappalli city, India. *Sustainable Cities and Society*, 116, 105865. <https://doi.org/10.1016/j.scs.2024.105865>
- Ghenai, C., Rejeb, O., Sinclair, T., Almarzouqi, N., Alhanaee, N., & Rossi, F. (2023). Evaluation and thermal performance of cool pavement under desert weather conditions: Surface albedo enhancement and carbon emissions offset. *Case Studies in Construction Materials*, 18, e01940. <https://doi.org/10.1016/j.cscm.2023.e01940>
- Ghoniem, M., Fahmy, A., & Kamel, T. M. (2025). Evaluating urban surface materials: Albedo optimization and shading for pedestrian thermal comfort in hot-arid environments. *Civil Engineering and Architecture*, 13(6), 4331–4352. <https://doi.org/10.13189/cea.2025.130616>
- Gidey, E., & Mhangara, P. (2025). Improving spatial modeling framework to assess the impact of vegetation cover, water content, and surface temperature on urban heat island effects in Johannesburg, South Africa. *Discover Environment*, 3(1), 74. <https://doi.org/10.1007/s44274-025-00264-0>
- He, Q., & Reith, A. (2023). A study on the impact of green infrastructure on microclimate and thermal comfort. *Pollack Periodica*, 18(1), 42–48. <https://doi.org/10.1556/606.2022.00668>
- Huang, C., Liu, K., Ma, T., Xue, H., Wang, P., & Li, L. (2025). Analysis of the impact mechanisms and driving factors of urban spatial morphology on urban heat islands. *Scientific Reports*, 15, 18589. <https://doi.org/10.1038/s41598-025-04025-0>
- Jandaghian, Z., Lacasse, M., & Gaur, A. (2025). Solar Reflectance Index of Building Envelope Materials: A Comparative Review of North American and European Standards and Long-Term Performance. *Buildings*, 15(6), 888. <https://doi.org/10.3390/buildings15060888>
- Kafy, A. A., Alsulamy, S., & Alsaleh, A. M. (2026). Escalating heat hazard risk in arid urban environments: A two-decade assessment of thermal stress patterns and health risks using UTCI and WBGT indices in Riyadh, Saudi Arabia. *Natural Hazards*, 122, 156. <https://doi.org/10.1007/s11069-025-07930-9>
- Kaushik S., A. S., & Amraotkar, S. (2026). Analyzing the effects of orientation, window size and position on solar heat gain for four Indian cities. *Science, Engineering and Health Studies*, 20, 26040001. <https://doi.org/10.69598/sehs.20.26040001>
- Lin, P., Song, D., & Qin, H. (2021). Impact of parking and greening design strategies on summertime outdoor thermal condition in old mid-rise residential estates. *Urban Forestry & Urban Greening*, 63, 127200. <https://doi.org/10.1016/j.ufug.2021.127200>
- Nutakki, T.U.K., Kazim, W.U., Alamara, K., Salameh, T., & Abdelkareem, M.A. (2023). Experimental Investigation on Aging and Energy Savings Evaluation of High Solar Reflective Index (SRI) Paints: A Case Study on Residential Households in the GCC Region. *Buildings*, 13(2), 419. <https://doi.org/10.3390/buildings13020419>
- Pachauri, R., & Kaushik S., A. S. (2025). A comparative evaluation of the effectiveness of glazed and open balconies in low-rise residences in moderate climates via field measurements and simulations. *Science, Engineering and Health Studies*, 19, 25040004. <https://doi.org/10.69598/sehs.19.25040004>
- Parison, S., Chaumont, M., Kounkou-Arnaud, R., Long, F., Bernik, A., Da Silva, M., & Hendel M. (2023). The effects of greening a parking lot as a heat mitigation strategy on outdoor thermal stress using fixed and mobile measurements: case-study project “tertiary forest.” *Sustainable Cities and Society*, 98, 104818. <https://doi.org/10.1016/j.scs.2023.104818>
- Patel, P., & Kaushik, A. S. (2023). The impact of microclimate on energy performance of office buildings within urban contexts located in a composite climate, the city of Indore. *IOP Conference Series: Earth and Environmental Science*, 1210, 012007. <https://doi.org/10.1088/1755-1315/1210/1/012007>
- Pattnaik, N., Rahman, M. A., & Pauleit, S. (2025). Urban vegetation structure and composition influence pedestrian thermal comfort in public spaces: A case study in Munich. *Urban Forestry & Urban Greening*, 114, 129162. <https://doi.org/10.1016/j.ufug.2025.129162>
- Peter, A., & Kaushik, S. A. S. (2024). A study on the impact of courtyard vegetation on its thermal comfort performance in an educational building of warm and humid climates. *Science, Engineering and Health Studies*, 18, 24040011. <https://doi.org/10.69598/sehs.18.24040011>
- Rachidi, A., Mounir, S. H., Sghir, S., & Lebaut, S. (2026). Urban albedo interventions reshape thermal comfort: A multiscale analysis of heat island, comfort, and energy effects in semi-arid Marrakesh. *Sustainable Cities and Society*, 136, 107090. <https://doi.org/10.1016/j.scs.2025.107090>
- Rodriguez, A., Wood, S., Carmeliet, J., Kubilay, A., & Derome, D. (2025). Local impact of trees on thermal comfort of pedestrians in streets. *Urban Climate*, 61, 102417. <https://doi.org/10.1016/j.uclim.2025.102417>
- Sen, S., Fernandez, J.P.R.M.-R., & Roesler, J. (2020). Reflective Parking Lots for Microscale Urban Heat Island Mitigation. *Transportation Research Record: Journal of the Transportation Research Board*, 2674(8), 663–71. <https://doi.org/10.1177/0361198120919401>
- Silva Nascimento, A. D., Silva, L.V.A.D., Lisboa, M.A.N., Oliveira Silva, A.D., Rodrigues Ferreira, M.F., Silva, S.C.F.D., Melo, M.J.V.D., Silva, A.C.V.D., & Júnior, J. T. C. (2025). How do visitors perceive the urban greenery microclimate in the city's only green space? A case study in Brazilian semi-arid. *Environmental Development*, 56, 101244. <https://doi.org/10.1016/j.envdev.2025.101244>
- Taleghani, M. (2018). The impact of increasing urban surface albedo on outdoor summer thermal comfort within a university campus. *Urban Climate*, 24, 175–184. <https://doi.org/10.1016/j.uclim.2018.03.001>
- Wei, Y.-Y., Cheng, C.Y., & Lin, T.-P. (2025). The influence of trees shade level on human thermal comfort and the development of applied assessment tools. *Landscape and Urban Planning*, 263, 105436. <https://doi.org/10.1016/j.landurbplan.2025.105436>
- Wang, C., Zhan, W., Liu, Z., Li, J., Li, L., Fu, P., Huang, F., Lai, J., Chen, J., Hong, F., & Jiang, S. (2020). Satellite-based mapping of the Universal Thermal Climate Index over the Yangtze River Delta urban agglomeration. *Journal of Cleaner Production*, 277, 123830. <https://doi.org/10.1016/j.jclepro.2020.123830>
- Zhang, T., Fu, X., Qi, F., Shen, Y., Xu, P., Tao, Y., Liu, T., & Song, Y. (2025). Optimizing pedestrian thermal comfort in urban street canyons for summer and winter: Tree planting or low-albedo pavements? *Sustainable Cities and Society*, 120, 106143. <https://doi.org/10.1016/j.scs.2025.106143>