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Urban Microclimate and Outdoor Thermal Comfort in Hot-Arid Cities: Simulation-Based Analysis in Egypt's New Administrative Capital

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Abstract

Outdoor thermal comfort is a critical determinant in the quality of urban life in hot-arid climates, particularly within newly developed governmental districts. This study employs a sequential mixed-methods approach to evaluate outdoor thermal comfort in the Governmental District of Egypt's New Administrative Capital. A systematic literature review following the PRISMA protocol, supported by bibliometric analysis, was conducted to identify effective climate-responsive mitigation strategies. The study area was classified into five thermal zones using K-means clustering to assess microclimatic conditions before and after the implementation of integrated design interventions. Simulation results based on Physiological Equivalent Temperature (PET), selected as the primary outdoor thermal comfort index due to its widespread application in ENVI-met-based hot-arid studies, reveal substantial thermal improvements across all zones, with improvements exceeding 10 °C in specific areas. Thermal stress classification indicates a shift from extreme heat stress to moderate and slight stress levels, indicating the thermal mitigation potential of the applied interventions. The findings provide a zone-based analytical framework with potential applicability to climate-responsive urban design in comparable hot-arid environments.

Keywords: Outdoor thermal comfort; hot-arid climate; climate change adaptation; urban microclimate; ENVI-met simulation; zone-based analysis; new administrative capital in Egypt; thermal stress classification.

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1. INTRODUCTION

Urbanization and climate change have exacerbated the Urban Heat Island (UHI) effect, increasing outdoor thermal discomfort in hot-arid climates. High temperatures in cities not only affect human health and well-being but also increase the energy demand for cooling systems (Oke 1987; Santamouris 2020). Consequently, mitigating urban heat is essential for promoting sustainable, livable, and resilient cities. Public open spaces play a key role in sustainable urban development. They support pedestrian movement, encourage outdoor social and economic activities, and contribute to urban vitality (Hakim et al. 1998; Hass-Klau 1993; Jacobs 1972; Whyte 1988). Ensuring thermal comfort in these spaces is particularly important in the Egyptian context, as extended periods of high temperatures often limit the usability of outdoor spaces and increase cooling loads in surrounding buildings (Makaremi et al. 2012).

Numerous studies have examined the potential of heat mitigation strategies such as increasing vegetation, providing shading structures, and using high-albedo materials to enhance thermal comfort in outdoor spaces (Akbari et al. 2016; Taleghani 2018). However, a considerable portion of existing research has focused on temperate climates or simplified urban models, with limited studies that examine realistic urban spaces in hot-arid regions such as Egypt, and offering zone-specific performance evaluations (Middel et al. 2018; Salata et al. 2017; Taleghani 2018). To capture localized microclimatic variability within the study area, this study introduces a thermal zoning approach using K-means clustering (Hartigan and Wong 1979) to identify spatially distinct microclimatic patterns and support targeted climate-responsive intervention strategies.

Aligned with Egypt Vision 2030, which emphasizes climate resilience and environmental sustainability in urban development (Ministry of Planning and Economic Development 2021), this study investigates the outdoor thermal performance of a public space in the Governmental District of Egypt’s New Administrative Capital. A two-step methodology was used: first, assessing current thermal conditions to identify critical areas exposed to heat stress and subsequently to apply multiple climate-responsive mitigation strategies derived from the systematic literature review findings to enhance thermal comfort. The study area was divided into five thermal zones with similar microclimatic characteristics to enable local comparative analysis. Accordingly, the study aims to develop and test a zone-based analytical framework for evaluating and improving outdoor thermal comfort in hot-arid public spaces, while deriving practical climate-responsive urban design recommendations for comparable environments.

2. SYSTEMATIC LITERATURE REVIEW

A systematic literature review was conducted to explore recent developments in outdoor thermal comfort research in urban environments, particularly in hot-arid regions. The review was undertaken to inform the simulation-based assessment phase of this study through evidence-based design strategies. The review aimed to identify commonly applied thermal mitigation strategies, examine their reported effectiveness, and classify methodological approaches adopted in relevant studies. To ensure methodological rigor and transparency, the review followed the PRISMA 2020 framework (Chaudhuri and Kumar 2022; Fu et al. 2022; Li et al. 2022; Moher et al. 2009; Page et al. 2021) and was complemented by bibliometric analysis. The overall review process was structured into five components: data collection, PRISMA screening, bibliometric analysis, publication trends and dataset characteristics, and data classification.

2.1. Data Collection

The literature search was conducted across two major scientific databases: Web of Science (WoS) Core Collection and Scopus, selected due to their comprehensive coverage of peer-reviewed publications in architecture, urban climate, and environmental design research. Bibliometric analysis was performed using VOSviewer version 1.6.19 to identify thematic research trends and keyword co-occurrence patterns within the selected literature (Arruda 2022; Kirby 2023; Van Eck and Waltman 2010). The overall literature review workflow is illustrated in Figure 1.

2.2. The PRISMA Framework

The PRISMA 2020 framework was adopted and visually adapted to suit the specific screening structure of this review while maintaining its core principles of transparent and systematic literature selection. The review process was organized into three sequential stages: identification, screening and exclusion, and final inclusion, as illustrated in Figure 2. The literature search was conducted on April 23, 2025, targeting studies published between 2015 and 2025 to extract recent developments in simulation-based and experimental research related to outdoor thermal comfort in hot climates. Each stage of the review process was carefully designed to ensure a systematic and focused selection of relevant studies.

The process began with the identification stage, where a comprehensive search was conducted in both the Web of Science (WoS) Core Collection and Scopus databases using basic search mode. The following search term was used: (Outdoor Thermal Comfort) AND (urban greenery OR green facade OR sky view factor OR urban space OR

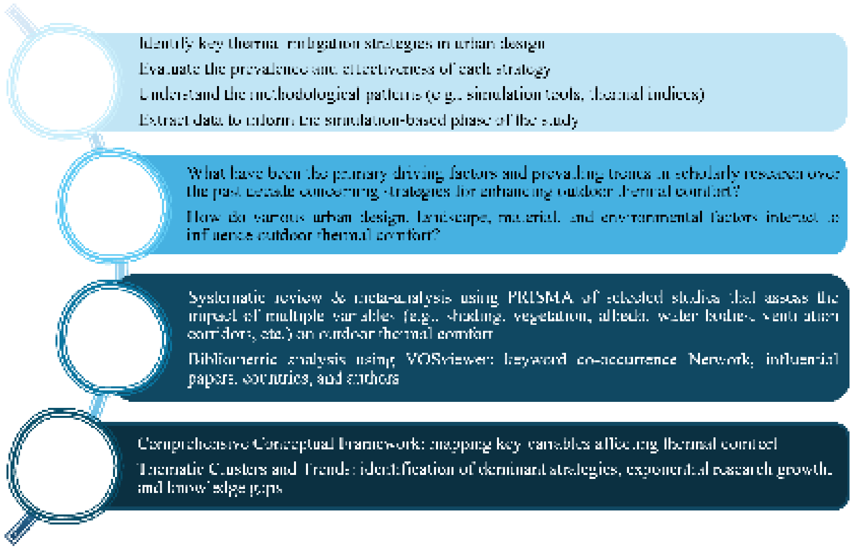


Figure 1. The overall literature review workflow

urban form OR water surface OR thermal indices OR albedo OR shading). The initial search yielded 1,703 records from the WoS database and 1,941 records from the Scopus database, resulting in a total of 3,644 identified records. After limiting the search to studies published between 2015 and 2025, the number of relevant records decreased to 1,485 in WoS and 1,862 in Scopus, yielding 3,347 studies for the next stage. Duplicate screening was then performed across both databases, resulting in the removal of 8 duplicate records.

In the screening and exclusion stage, records were filtered sequentially according to predefined eligibility criteria, including publication language, document type, disciplinary relevance, and thematic relevance to the scope of this study. Screening and eligibility assessment were conducted manually by the first author through title, abstract, and full-text review. Studies not written in English, publications other than research articles or review papers, and studies unrelated to engineering, architecture, or urban design were excluded. After applying these criteria, the number of remaining studies decreased to 455 studies in WoS and 148 in Scopus.

A final dataset of 603 studies was maintained for systematic and bibliometric analysis. These studies provided the basis for identifying key methodological

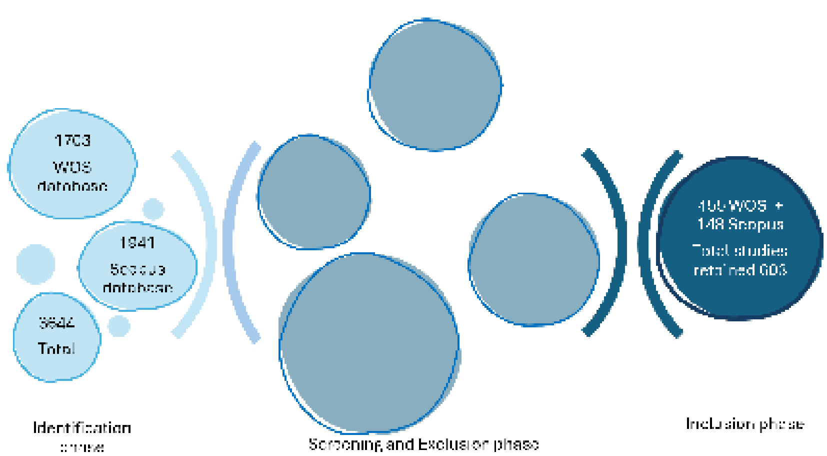


Figure 2. PRISMA-based flow diagram showing the identification, screening, and inclusion phases.

trends, dominant mitigation strategies, and research gaps in the field of outdoor thermal comfort. Figure 2 shows the detailed exclusion categories and the number of records for each stage.

The studies examined formed the basis for bibliometric mapping and quantitative classification, enabling the extraction of key themes and supporting the selection of strategies to be tested in the simulation case study.

1.3. Bibliometric Analysis

The final dataset of 603 selected studies was analyzed using VOS-viewer software (version 1.6.19) to generate bibliometric maps illustrating keyword co-occurrence patterns within the outdoor thermal comfort literature (Li et al. 2022). The resulting keyword co-occurrence map, shown in Figure 3, highlights the most frequently occurring and interconnected research terms within the selected literature. Frequently recurring keywords included ENVI-met, outdoor thermal comfort, thermal comfort, urban heat island, microclimate, urban microclimate, and Physiological Equivalent Temperature (PET), reflecting the dominant methodological and thematic directions within the field. In the bibliometric map, node size represents keyword frequency, while connecting lines indicate co-occurrence relationships between terms.

The analysis identified eight thematic keyword clusters representing major research streams in thermal comfort. The most prominent clusters were associated with simulation-based urban microclimate assessment (e.g., ENVI-met, urban microclimate), human-centered thermal comfort evaluation (e.g., outdoor thermal comfort, PET, human thermal comfort), and urban-scale heat mitigation research (e.g., urban heat island). Collectively, these thematic groupings informed the subsequent classification and filtering of studies for detailed analytical review.

1.4. Publication Trends and Dataset Characteristics

Nasrollahi et al. (2020) emphasized that early research on outdoor thermal comfort began in the late twentieth century. The growing development of microclimate

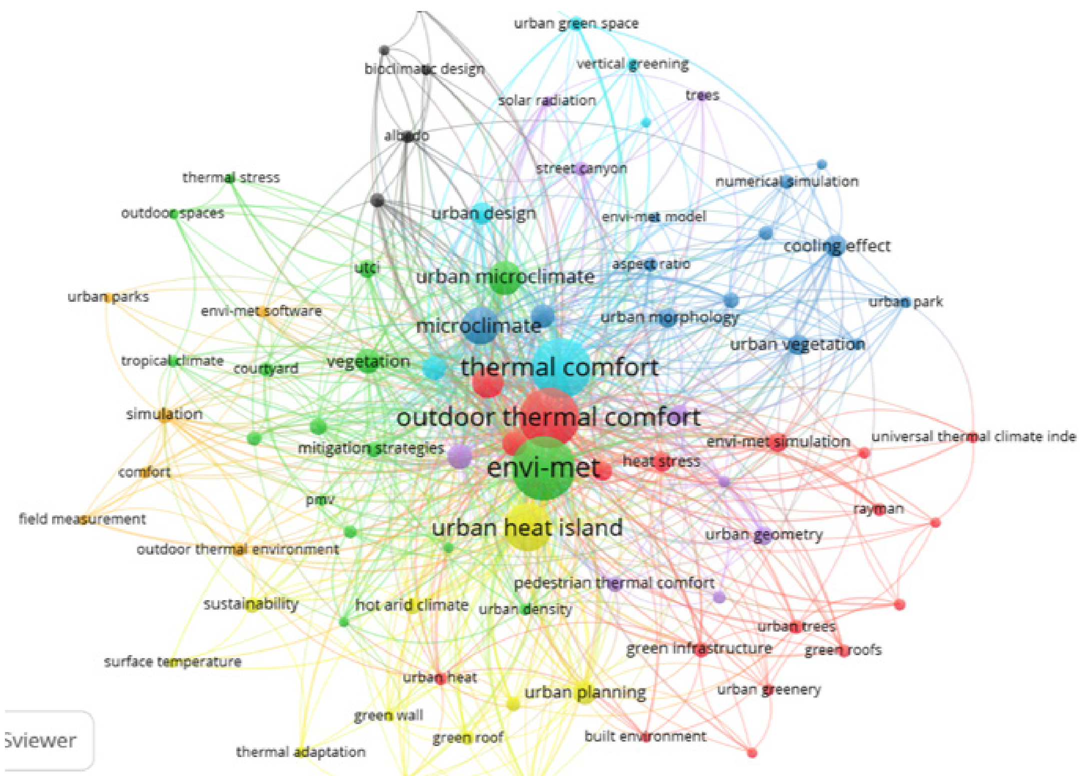


Figure 3. VOS-viewer keyword co-occurrence map of the selected literature, illustrating keyword frequency, co-occurrence relationships, and thematic clustering within outdoor thermal comfort research.

simulation tools, particularly since 2010, has led to a significant rise in simulation-based studies, often supported by empirical observations in real urban environments.

To provide a contextual view of the development of outdoor thermal comfort research, the final dataset of 603 studies was analyzed in depth in terms of publication trends, document types, and database distribution. As illustrated in Figure 4a, publication output in this field has shown a clear upward trend over the past decade, increasing from 27 publications in 2015 to a peak of 78 publications in 2024. The decrease in 2025 (48 publications) was[GG1.1][NA1.2] due to the timing of data collection, as publications from that year were still being indexed at the time of the review.

Regarding document type, Figure 4b indicates that the majority of included studies were research articles (n = 539), while review papers constituted a smaller proportion (n = 64), reflecting the prevailing empirical nature of the field. Database distribution analysis (Figure 4c) showed that 455 studies were indexed in WoS and 148 in Scopus after duplicate removal and screening (n = 8).

Overall, these trends demonstrate the rapid growth and increasing methodological maturity of outdoor thermal comfort research, supporting the decision to prioritize recent literature in the subsequent detailed analytical phase.

1.5. Data Classification

To maintain analytical relevance while capturing recent methodological developments in outdoor thermal comfort research, the detailed analytical review was limited to studies published during the last three years of the dataset (2023–2025), resulting in a subset of 192 studies. This temporal focus was adopted to prioritize the most recent simulation practices, evaluation methods, and climate-responsive design strategies while maintaining a sample broad enough for comparative analysis.

Following this temporal filtering, an additional screening stage was conducted to identify studies most relevant to the objectives of the present research. Studies were excluded if they lacked applied thermal mitigation strategies, did not provide quantitative performance data, relied only on descriptive or observational approaches, focused on large-scale urban patterns

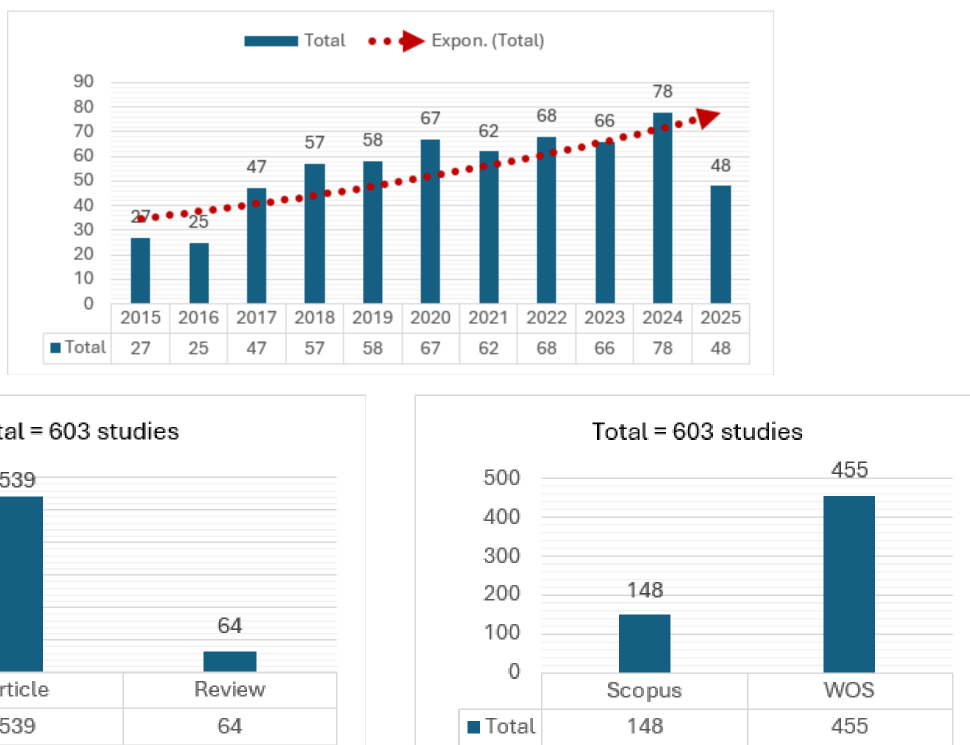


Figure 4. Overview of the characteristics of the reviewed studies: a – annual distribution of publications showing the temporal growth of research in this field; b – classification of documents by type; and c – distribution of studies across different scientific databases.

rather than micro-scale, or were conducted in climatic contexts not comparable to hot-arid environments. Additional exclusion criteria included studies relying only on field measurements without simulation-based intervention testing, those lacking baseline pre-intervention data, studies using limited or non-standard thermal comfort indicators without sufficient comparative value, and studies providing an insufficient quantitative description of the interventions applied. Other studies were considered narrow in scope, such as focusing only on a single courtyard, semi-private spaces, or a specific type of tree, which reduced the generalizability of the results. In some cases, results were presented without comprehensive before-and-after datasets, or were based on overly simplified or isolated interventions, which limited their contribution to comparative analysis. After applying these criteria, 30 studies were retained as the final analytical sample for in-depth critical review. These selected studies provided the analytical basis for identifying applicable mitigation strategies, evaluating intervention performance, and informing the design framework adopted in the subsequent simulation-based case study.

The selected studies were subsequently classified according to the thermal mitigation strategies investigated, as illustrated in Figure 5. Integrated strategies represented the most frequently examined category, with 13 studies combining multiple interventions such as vegetation, shading devices, material modification, and water features. Vegetation-based strategies also appeared either as independent interventions or in combination with other design measures, highlighting their widespread application in diverse urban contexts. Other strategies, including urban morphology modifications, improved orientation, water spray systems, and vegetation distribution patterns, were addressed less frequently in the reviewed literature. The prevalence of integrated approaches in the selected studies suggests an increasing research emphasis on multi-component intervention frameworks for outdoor thermal comfort enhancement. Accordingly, this study adopted an integrated mitigation approach as the basis for the proposed intervention scenario, with individual strategies selected and spatially allocated according to the climatic and morphological characteristics of the study area.

In addition to strategy classification, the selected studies were analyzed according to thermal comfort indicators, simulation tools, and evaluation methods used, as illustrated in Figure 6. Among thermal comfort indices, Physiological Equivalent Temperature (PET) was the most frequently reported indicator, representing 44% of the selected studies, followed by PMV and UTCI. This distribution reflects the widespread application of PET in outdoor thermal comfort studies, particularly in simulation-based urban microclimate research. Regarding simulation tools, ENVI-met was the most frequently utilized microclimate simulation platform, appearing in 80% of the selected studies either as a standalone tool or in combination with complementary software such as RayMan or Ladybug Tools. This reflects its widespread use in simulation-based outdoor thermal comfort research. Regarding the methodology used, 60% of the reviewed studies relied exclusively on simulation-based evaluation, 7% used field measurements only, and 33% combined simulation with empirical measurements. While simulation-based approaches dominate due to their flexibility in evaluating multiple design scenarios, the integration of field measurements remains an important method for validating results whenever possible.

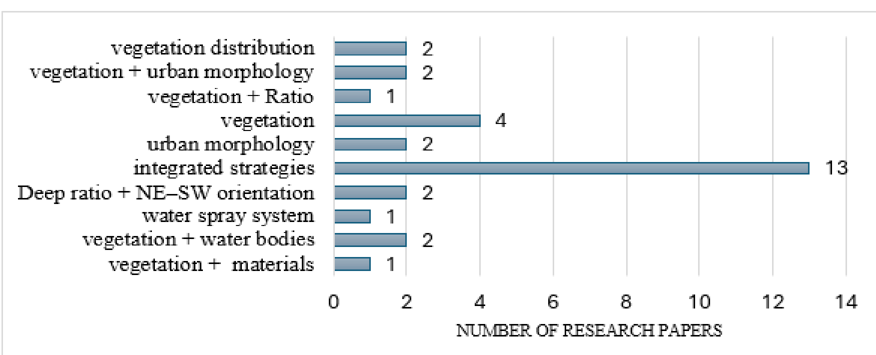


Figure 5. Distribution of thermal comfort improvement strategies in the 30 selected studies.

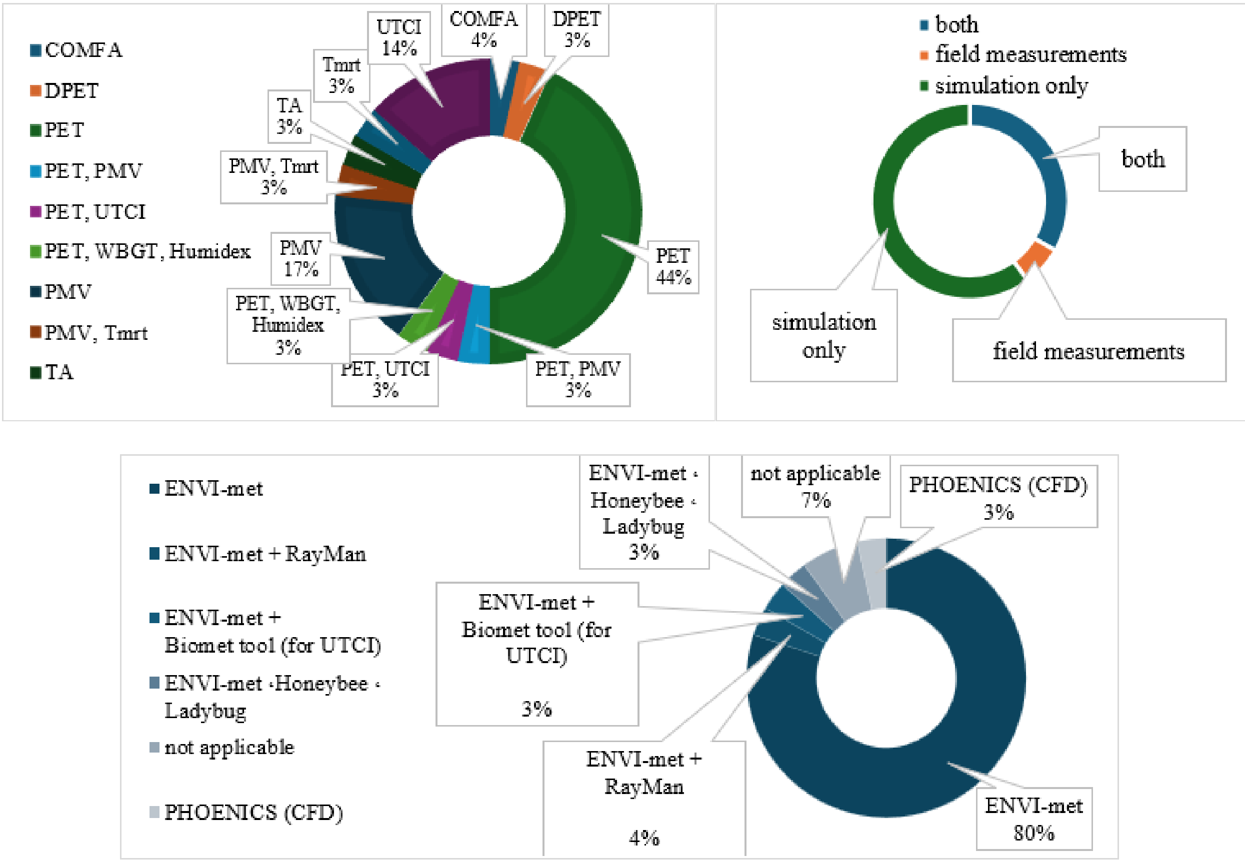


Figure 6. Distribution of methodological approaches in the reviewed studies: a – thermal comfort indices applied; b – measurement approaches; and c – simulation tools employed.

Collectively, these findings contributed to shaping the methodological framework of the present study, supporting the selection of simulation-based evaluation using ENVI-met and the inclusion of PET as a principal thermal comfort indicator, with final methodological choices further justified according to the specific objectives and climatic context of the case study.

2. RESEARCH METHODOLOGY

This research adopts a sequential mixed-methods methodology integrating a systematic literature review and simulation-based case study analysis to evaluate climate-responsive heat mitigation strategies in outdoor urban spaces. As illustrated in Figure 7, the research framework consists of two complementary components: (1) evidence synthesis through systematic literature review to identify prevalent mitigation strategies, evaluation methods, and simulation approaches; and (2) simulation-based application of these findings within a representative case study through thermal zoning, zone-responsive intervention allocation, and comparative microclimatic performance evaluation. The outputs of both components were integrated through post-processing and spatial comparative analysis to develop context-specific design recommendations for improving outdoor thermal comfort in hot-arid urban environments.

2.1. Literature-Based Simulation Framework

The systematic literature review presented in the previous section established the evidence base that guided the simulation phase of this study. Specifically, the review contributed to the selection of mitigation strategies, thermal comfort indicators, simulation tools, and broader methodological criteria adopted in the case study analysis. In addition, the review supported the development of a zone-responsive intervention framework by identifying common multi-strategy mitigation approaches and commonly applied evaluation methods in recent outdoor thermal comfort research. These findings were subsequently translated into the simulation design, thermal zoning process, and intervention allocation strategy adopted in the present study.

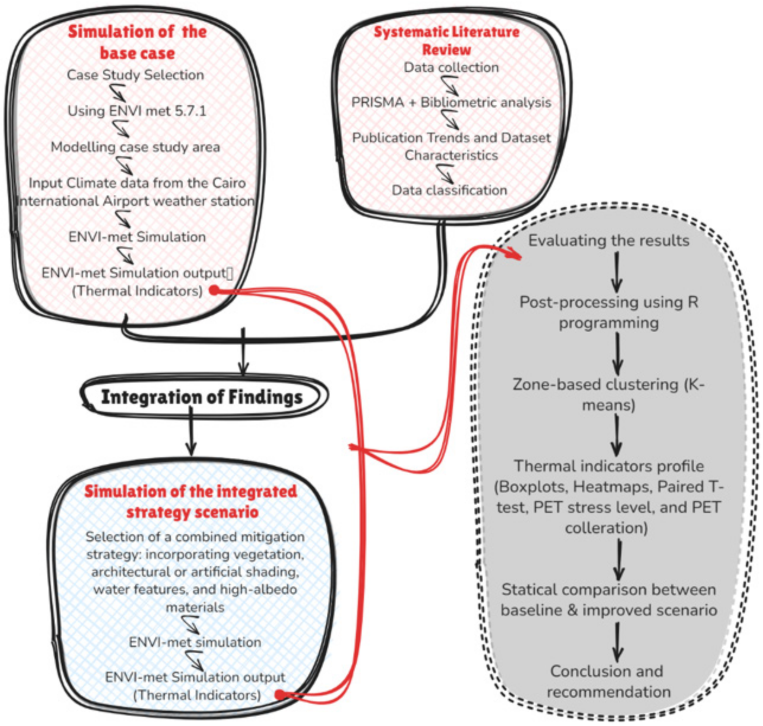


Figure 7. Methodological framework

2.2. Case Study Area Description

As a rapidly urbanizing developing country, Egypt faces increasing challenges as a result of climate change, with projections indicating that average annual temperatures may rise by up to 5.6°C between 1990 and 2100 under high-emission scenarios (Fahmy et al., 2020). In this context, Egypt's New Administrative Capital (NAC) is located east of Cairo, within a hot-arid climatic zone characterized by extremely hot summers, low relative humidity (RH), and intense solar radiation (SR). These climatic conditions increase outdoor heat stress and highlight the need for climate-responsive urban design strategies.

The Governmental District of the NAC was selected as a case study due to its strategic national importance as Egypt's major administrative center and its representative contemporary urban planning typology for large-scale governmental developments in hot-arid environments. Despite its formal urban organization, many outdoor spaces within the district remain highly exposed to SR, with limited shading and vegetation, reducing pedestrian thermal comfort during peak summer periods.

The Governmental District extends over approximately 1.5 million m² (150 acres), of which 28% is allocated to built-up areas and 72% is allocated to open areas. It includes 10 ministerial complexes containing 34 ministries, the Cabinet headquarters, and a central government axis, with a large plaza in the middle. Within the Governmental District, a representative sub-area of approximately 250,000 m² (about 60 acres) was selected for detailed simulation analysis, as illustrated in Figure 8. The selected study area reflects the existing built and landscaping conditions at the time of the study and represents an already constructed and operational part of the Governmental District. The area includes pedestrian pathways, paved open spaces, scattered landscaped areas, governmental buildings, and outdoor gathering spaces. The existing landscape configuration is dominated by hardscape surfaces with limited vegetation coverage, mainly consisting of palm trees and grass areas, in addition to scattered fountains and some wooden pergolas. This configuration results in significant solar exposure and outdoor heat stress during peak summer daytime conditions. Detailed characteristics of the base case configuration are summarized in Table 2. Building heights within the study area range from approximately 5 to 40 m (1–9 storeys), generating varied microclimatic conditions through differences in solar exposure, wind flow, and radiant heat exchange. The selected area includes a range of urban spatial configurations, including open plazas, semi-enclosed courtyards, and enclosed internal spaces, thereby representing a wide range of urban spatial and microclimatic conditions within the district. These spatial variations support comparative analysis of localized thermal performance and effective intervention across different urban morphologies.

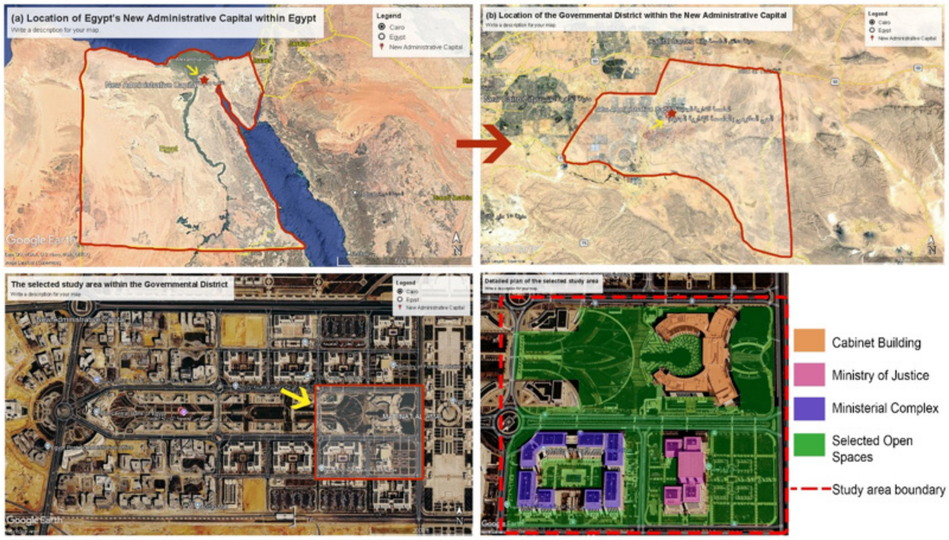


Figure 8. Multi-scale spatial context of the selected case study area: (a) location of Egypt's New Administrative Capital within Egypt; (b) location of the Governmental District within the New Administrative Capital; (c) the selected study area within the Governmental District; and (d) detailed plan of the selected study area showing the surrounding buildings and urban open spaces analysed in the simulation. (Base satellite imagery source: Google Earth Pro)

Figure 9. Google Maps images of the study area illustrating the existing landscape conditions.

The study area was selected based on its central location within the Governmental District, representation of different urban spatial configurations, active pedestrian use by public employees and visitors, and its suitability for implementing climate-responsive mitigation interventions, including shading, vegetation, and material modifications. Figure 9 shows real images of the study area illustrating the existing landscape conditions.

2.3. Simulation Setup (ENVI-Met)

Microclimatic simulations were performed using ENVI-met version 5.7.1, a three-dimensional non-hydrostatic computational fluid dynamics model specifically designed to simulate surface–plant–air interactions within urban environments. ENVI-met was chosen due to its widespread application in outdoor thermal comfort and urban microclimate studies, as identified in the previous literature review, and its demonstrated ability to model micro-scale interactions among urban morphology, vegetation, surface materials, and atmospheric conditions (Bruse and Fleer 1998; Halder et al. 2025).

The simulation area covered an area of 500 m × 500 m and was divided into 50 × 50 × 40 grid cells with a horizontal resolution of 10 m. This grid resolution was selected to balance spatial representation of the large urban study area with computational feasibility while maintaining sufficient detail to capture localized microclimatic variations across the site.

Meteorological climatic conditions were derived from the Cairo International Airport weather station (WMO code: 623660/ETMY), which was selected as an available source of continuous hourly meteorological data representing long-term regional climatic conditions of the study area. Cairo International Airport data were adopted due to the absence of long-term meteorological monitoring stations within Egypt's New Administrative Capital (NAC), while both locations share comparable regional hot-arid climatic characteristics, including high summer temperatures, low precipitation, and intense SR. Dynamic limit conditions including air temperature (T-air), RH, wind speed (WS), wind direction (WD), and SR were applied using ENVI-met Forcing Manager.

Climatic analysis of the EPW weather data obtained from Cairo International Airport indicates that July represents one of the hottest and most thermally stressful periods of the year within the regional hot-arid climate context. Peak daytime air temperatures during July frequently exceed 35 °C, accompanied by intense SR, high diffuse radiation levels, low precipitation, and extended heat exposure conditions. These combined climatic characteristics contribute significantly to outdoor thermal discomfort and increased mean radiant temperature (MRT) within urban spaces. Therefore, 15 July 2024 was selected as a representative peak summer day for evaluating outdoor thermal stress under critical climatic conditions. The main meteorological characteristics of the selected simulation day are summarized in Table 1. The simulation was conducted over a 24-hour period starting at 06:00 local time, selected to represent peak summer thermal conditions within the climatic context of Egypt's New Administrative Capital. Detailed comparative analysis focused on the 14:00 period, which corresponds to the approximate time of maximum daytime thermal stress in the study area during summer, when SR and MRT typically approach their daily peak values.

Parameter	Value
Potential air temperature	33 °C
Relative humidity	11.4 g/kg
Direct Shortwave Radiation	712 W/m²
Diffuse Shortwave Radiation	380 W/m²
Wind speed	6.5 m/s
Precipitation	0 mm

Table 1. Meteorological characteristics of the selected simulation day (15 July 2024 at 14:00) derived from Cairo International Airport EPW data.

Feature	Base Case Configuration	Improved Scenario Configuration
Vegetation	Trees: 01PLDS Palm trees (dense, small trunk, 5 m height): ~9.16% of total area	Vegetation coverage increased to ~21.6% of total area - Inclusion of two shade-providing tree species: London Plane Tree and Silver Maple.
	Grass: (25 cm - average dense): ~26.7%	Grass coverage slightly reduced due to replacement by additional built blocks
	Buildings with moderate wall insulation, covering ~18.16%	Increased to ~18.9% through the addition of small-scale built blocks (5 m high, 10 × 10 m footprint), accounting for ~1% of total site area and ~4% of built-up area.
Water Features	Existing fountains (3.33% of total area)	Increased to 3.9% with the addition of a central fountain in the main plaza
Ground Materials	Asphalt, concrete, and marble paving	Replacement of asphalt with high-albedo light-coloured concrete pavement
artificial shading	Some wooden pergolas	Increase their number in the squares and on both sides of the walkways
Simulation Time	24 hours starting at 06:00 local time	Same as base case
Evaluation Time	14:00 (peak thermal stress)	Same as base case

Table 2.1. Comparison between the Base Case and Improved Scenario Configurations.

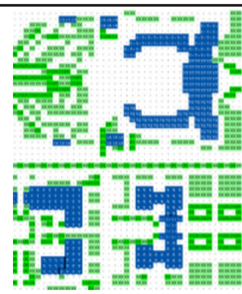
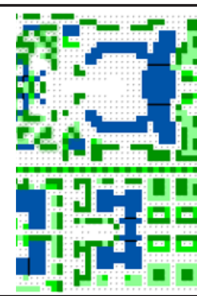
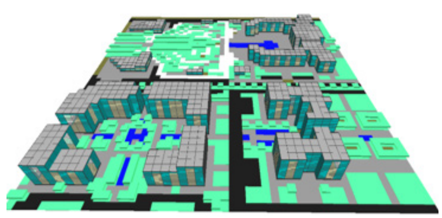
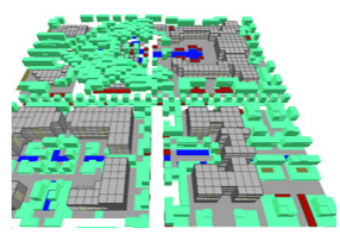
Model Domain for the Study Area		
		

Table 2.2. Comparison between the Base Case and Improved Scenario Configurations.

Two simulation scenarios were developed for comparative evaluation: (1) a baseline scenario representing the existing built and landscape conditions of the study area at the time of analysis, and (2) an improved design scenario including climate-responsive mitigation interventions. The detailed characteristics of both scenarios are summarized in Table 2.1 and 2.2.

2.4. Thermal Zones Analysis

To capture spatial variation in baseline microclimatic conditions across the study area, thermal zoning analysis was performed using the K-means clustering algorithm, an unsupervised machine learning technique that divides observations into groups by reducing variation within clusters (James et al., 2013). This method has been adopted to identify spatially disparate groups of locations sharing similar thermal and microclimatic characteristics, enabling localized evaluation of heat stress and targeted intervention planning.

Clustering was applied to the baseline ENVI-met simulation output at 14:00, which corresponds to the peak daytime heat stress period within the study area. Before clustering, all variables were standardized to eliminate scale bias resulting from differences in measurement units and numerical ranges. The clustering process was based on six microclimatic and thermal comfort variables: T-air, PET, MRT, RH, WS, and SR. These variables were selected to include both

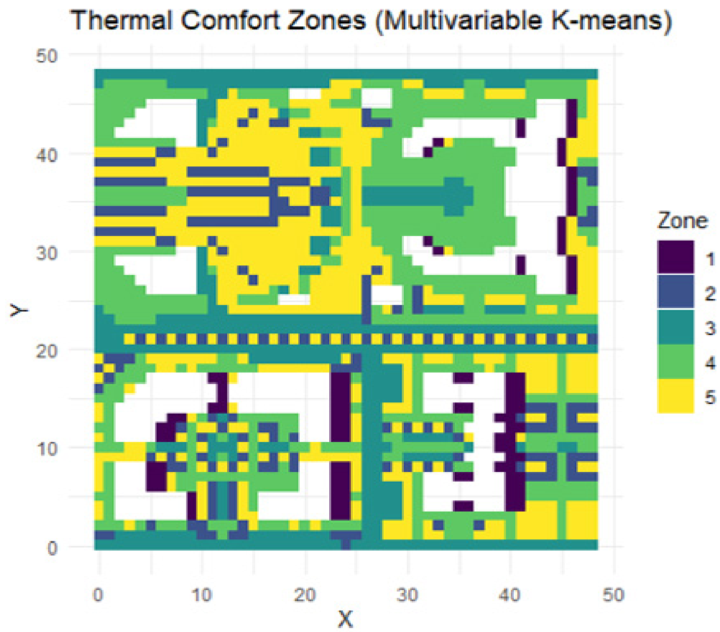


Figure 10. Spatial distribution of the five thermal zones identified through K-means clustering based on six baseline microclimatic variables.

objective microclimatic conditions and the integrated human thermal comfort response across the study area. This method has been adopted to identify spatially disparate site groups that share similar precise thermal and climatic characteristics, enabling local evaluation of heat stress and targeted planning of interventions.

The optimal number of clusters was determined using the Elbow Method based on a within-cluster sum of squares (WSS) analysis, a commonly used method for identifying an appropriate K-means cluster solution by balancing variance reduction against model complexity (James et al., 2013). The resulting Elbow curve indicated that a five-cluster solution provided the most appropriate balance between cluster coherence and ease of interpretation. The resulting thermal zoning map was subsequently used to guide the spatial distribution of climate-responsive mitigation interventions according to the dominant thermal characteristics of each zone. The resulting zoning classification is presented in Figure 10, while the quantitative characteristics of each thermal zone are discussed later.

2.5. Zone-Based Intervention Distribution

After the thermal zoning analysis of the baseline simulation results, mitigation measures were spatially allocated according to the specific microclimatic and morphological characteristics of each identified thermal zone. Rather than applying a uniform intervention package across the entire study area, a differentiated zone-responsive approach was adopted to ensure that each zone received interventions proportional to its specific thermal stress drivers, spatial constraints, and improvement potential. The selection of interventions was informed by both the thermal zoning results and the evidence-based mitigation strategies identified through the systematic literature review.

Zone 1, which includes areas adjacent to buildings and already benefits from substantial building-generated shading, was maintained as a reference condition without additional interventions. In this zone, the main goal was to maintain existing favorable shading conditions without suggesting unnecessary modifications.

Zone 2, representing semi-shaded transition zones located near existing palm trees and vegetated corridors, received moderate interventions aimed at enhancing shading continuity and reducing radiant heat exposure.

These measures included adding shading structures, increasing vegetation, and local modifications to surface materials.

Zone 3, characterized by open streets and high surface heat accumulation, was addressed primarily through material-based intervention. Existing asphalt pavements were replaced with high-albedo, light-colored concrete to reduce solar heat absorption and surface temperature.

Zone 4, classified as a highly exposed entrance plaza exposed to direct sunlight, received limited interventions, mainly limited to additional wooden shading structures. The extent of intervention in this zone was determined by the nature of its formal paving, the use of granite and marble finishes, and its proximity to major building entrances.

Zone 5, comprising large open plazas with minimal shading and high thermal exposure, underwent the most comprehensive intervention package. This included increased vegetation coverage, additional shading structures, incorporation of small-scale built shading elements (approximately 5 m in height) to modify local urban form and increase shaded areas and water features to enhance evaporative cooling.

This differentiated intervention framework enabled climate-responsive distribution of mitigation strategies based on localized environmental conditions rather than uniform site-wide application. It should be noted that the interventions were evaluated as integrated zone-based packages rather than isolated individual measures, in order to reflect realistic urban design constraints.

2.6. Post-Processing Statistical Tool and Evaluation Criteria

After completing ENVI-met simulations for both baseline and improved scenarios, the resulting datasets were exported as CSV format for post-processing and statistical analysis. All subsequent data processing, statistical testing, and graphical visualization were performed using programming language, an open-source statistical computing environment widely used for advanced data analysis and visualization (R Core Team 2024). Thermal performance evaluation focused on comparing baseline and post-intervention conditions across the pre-defined thermal zones. To evaluate the statistical significance of thermal improvements within each zone, paired t-tests were conducted between baseline and improved scenario outputs, with p-values < 0.05 considered statistically significant.

The evaluation focused mainly on reductions in Physiological Equivalent Temperature (PET) as one of the main indicators of outdoor thermal comfort, due to its widespread application in urban outdoor thermal comfort research, its compatibility with ENVI-met simulation outputs, and its ability to integrate multiple meteorological and physiological parameters into a single human-centered thermal comfort index (Höppe 1999; Mayer and Höppe 1987). Previous comparative reviews have shown that PET is among the most frequently applied thermal comfort indices in urban microclimate studies due to its suitability for pedestrian-level thermal assessment and its applicability within complex urban environments (Potchter et al. 2018). In addition, PET expresses thermal perception in °C, which facilitates interpretation and comparison with conventional T-air conditions for both researchers and urban designers (Johansson et al. 2014). Although the Universal Thermal Climate Index (UTCI) is also widely used in outdoor thermal comfort research, PET was considered more methodologically aligned with the ENVI-met simulation framework adopted in this study and more suitable for evaluating localized thermal conditions within hot-arid urban spaces (Bruse and Fleer 1998).

Changes in T-air and MRT were additionally evaluated to provide a complementary evaluation of microclimatic and physiological thermal improvements. To ensure temporal consistency and comparability, detailed evaluation was performed using simulation outputs at 14:00 local time, which corresponds to the identified peak daytime thermal stress period within the study area during the selected summer simulation day.

This integrated post-processing framework enabled quantitative evaluation of both the statistical significance of thermal improvements and their spatial variability across the identified thermal zones.

3. RESULTS AND ANALYSIS

This section presents ENVI-met simulation outcomes and subsequent statistical analyses comparing baseline and improved scenarios. The analysis evaluates the thermal performance of the proposed interventions across thermal zones predefined in the methodology, highlighting spatial variations in intervention effectiveness across the study area. Quantitative differences in key thermal comfort indicators, particularly PET and T-air, are examined and visualized through statistical graphs and spatial heatmaps. Statistical significance testing is additionally reported to provide quantitative evidence of intervention effectiveness and support interpretation of thermal improvement patterns.

3.1. Baseline Thermal Conditions Across Thermal Zones

As shown in Table 3, the thermal zoning analysis classified the study area into five distinct zones, each representing a specific set of microclimatic conditions and thermal exposure characteristics under baseline conditions. Zone 1 demonstrated the most thermally favourable conditions, recording the lowest SR (130 W/m²), MRT (40.0 °C), and PET (37.1 °C), mainly due to shading from surrounding buildings. Zone 2 represented semi-shaded transitional areas with moderate thermal exposure, with an average PET of 44.2 °C and TA of 31.6 °C. Zone 3, which mostly represents open streets, presented relatively high solar exposure but benefited from the highest WS among all zones (1.53 m/s), which partly mitigated the MRT (61.4 °C) and PET (44.8 °C). The highest levels of heat stress were recorded in Zone 4, which recorded the highest values of PET (49.3 °C), MRT (70.1 °C), and SR (1493 W/m²), indicating extreme radiant heat exposure in fully sun-exposed paved areas. Zone 5, representing wide open spaces with limited shading, recorded the highest TA (31.8 °C) and lowest RH (28.3%), together with PET values (47.8 °C), reflecting notable heat stress in expansive open plazas.

Overall, the baseline thermal zoning results demonstrated clear spatial variation in thermal conditions across the study area, highlighting the importance of site-specific mitigation strategies tailored to the dominant thermal stress characteristics of each zone.

3.2. Spatial Distribution of PET Before and After Intervention

To evaluate the spatial impact of the proposed mitigation interventions on outdoor thermal comfort, the spatial distribution of PET across the study area was analyzed for both baseline and improved scenarios at 14:00. Heat maps generated using R software from ENVI-met simulation outputs were used to visualize localized variations in thermal stress and identify areas of greatest thermal improvement. Figure 11 presents the resulting PET distributions of both scenarios. Under baseline conditions, PET values recorded a mean of 45.8 °C, ranging between 33.49 °C and 58.11 °C, with the highest levels concentrated in wide paved plazas and fully exposed corridors. These hotspots represent areas of extreme heat stress, reflecting the absence of shading, high SR, and limited vegetation. In contrast, the improved scenario demonstrates a significant reduction in convection, with mean PET decreasing to 42.7 °C

Cluster No.	Cluster Name	Count	T_air (°C)	PET	RH (%)	Wind (m/s)	SR (W/m²)	MRT (°C)	Zone Description
Zone 1	Spaces adjacent to buildings	111	31.0	37.1	29.5	1.15	130	40.0	Shaded areas near buildings or dense vegetation low radiation and high thermal comfort.
Zone 2	Semi-shaded spaces	221	31.6	44.2	28.8	1.34	781	56.6	Semi-shaded transitional spaces such as tree-lined paths or building perimeters.
Zone 3	Open street areas	432	31.5	44.8	29.0	1.53	1251	61.4	Open, ventilated street areas; exposed to high sun but mitigated by wind flow
Zone 4	Entrance plazas	620	30.8	49.3	29.9	1.23	1493	70.1	Fully sun-exposed paved surfaces; high radiant heat and low shading
Zone 5	Open plazas	581	31.8	47.8	28.3	1.43	1421	67.3	Open spaces with minimal shade; highest heat stress and solar exposure

Table 3. Quantitative Baseline Thermal Characteristics of the Identified Thermal Zones (14:00 Simulation Output)

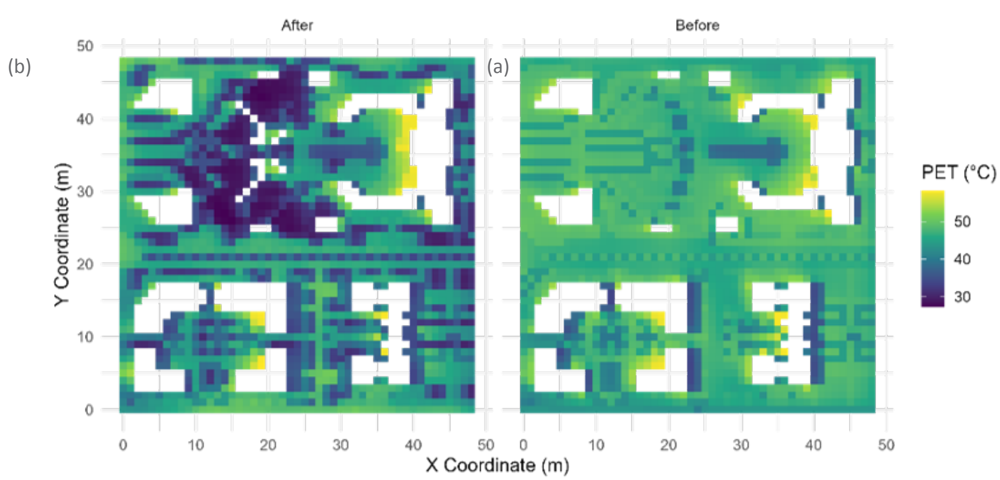


Figure 11. R-based heatmaps of PET spatial distribution at 14:00 under (a) baseline and (b) improved scenarios, generated from ENVI-met simulation outputs.

and values ranging between 27.29 °C and 58.28 °C, representing an overall decrease of approximately5.8 °C.

To further illustrate the magnitude and spatial distribution of thermal improvement, a differential PET map was generated by subtracting post-intervention PET values from baseline values in each grid cell (Figure 12). In this map, blue areas indicate decreases in PET and corresponding thermal improvement, whereas red areas indicate local increases in PET, and white areas reflect little or no thermal change after the intervention. The results reveal that the greatest PET reductions occurred in central plazas and vegetated corridors, particularly in zones that received combined shading and vegetation interventions. In contrast, areas subjected to limited or single-strategy interventions displayed relatively fewer thermal improvements.

Overall, the spatial PET analysis demonstrates significant simulated reductions in outdoor thermal stress across the study area, with the largest improvements observed in zones receiving multiple combined interventions within the proposed scenario.

3.3. Zone-Based Thermal Performance Comparison

Descriptive statistics of PET were calculated for each thermal zone under both baseline and improved scenarios, as shown in Table 4. The results demonstrate clear inter-zonal variation in thermal response, with all zones presenting reductions in PET after applying the proposed mitigation interventions. Zone 5 recorded the greatest improvement, with a PET reduction of 10.7 °C (22.4%), followed by Zone 2 with a reduction of 7.2 °C (16.2%). These zones received the most comprehensive intervention packages, including increased vegetation, shading structures, small building blocks (~5 m height),

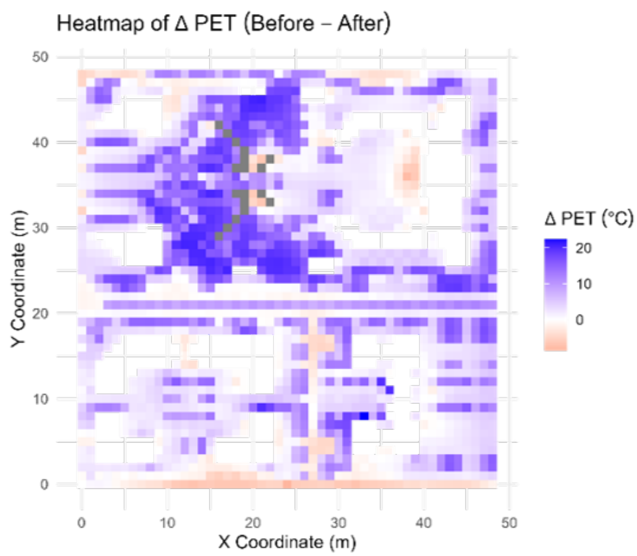


Figure 12. Spatial distribution of PET reduction (ΔPET = Baseline – Improved) across the study area following mitigation interventions.

Zone	Mean After	Mean Before	Median After	Median Before	SD After	SD Before	Absolute Change	Percentage Change
1	35.53	37.13	35.32	37.07	2.39	2.20	1.6	4.31
2	37	44.17	36.54	44.35	5.46	1.53	7.17	16.24
3	43.44	44.84	46.03	45.88	5.69	2.67	1.4	3.12
4	44.80	49.30	45.52	48.90	6.07	2.67	4.5	9.12
5	37.04	47.76	35.78	47.75	6.43	1.42	10.72	22.44

Table 4. Descriptive statistics of PET across thermal zones under baseline and improved scenarios.

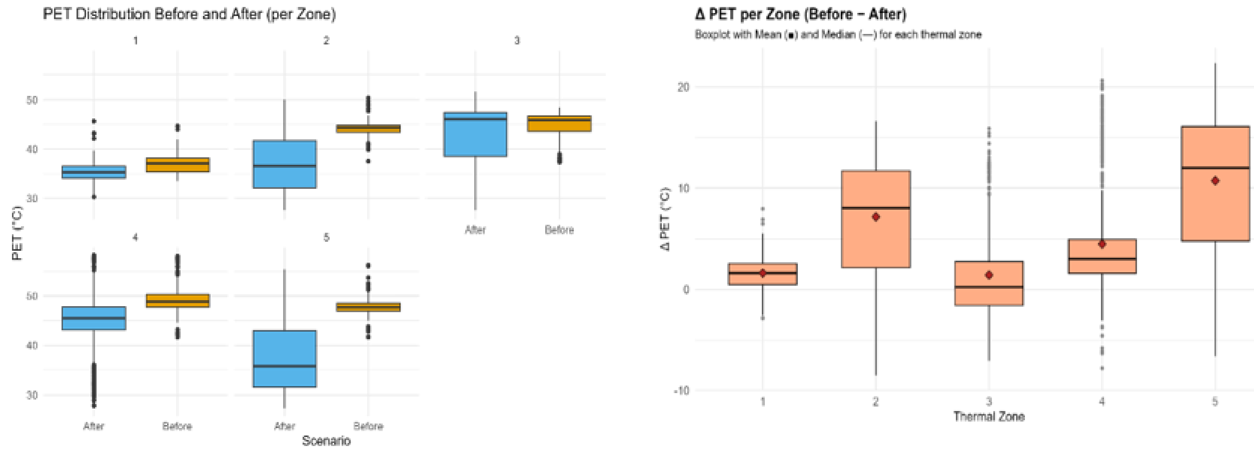


Figure 13. Boxplot comparison of PET values across thermal zones: a – distribution before and after interventions; and b –distribution of ΔPET (improvements)

(a) (b)

and water features. In contrast, Zone 3, which was limited to material replacement only, showed the lowest PET reduction of 1.4 °C (3.1%), compared to zones that received multiple interventions in the improved scenario.

Additional distribution analysis using boxplots (Figure 13) illustrates variation in PET response across thermal zones. Median PET values decreased across all zones, with significant reductions observed in Zones 2 and 5, where median decreases exceeded 8 °C. However, standard deviation values increased significantly in these two regions, indicating greater thermal variation within a single region after the intervention. This increased dispersion reflects heterogeneous local cooling effects resulting from the spatially differentiated distribution of shading, vegetation, and surface treatments. These results are presented in the supplementary boxplots as shown in Figure 13a and Figure 13b, which highlight the decrease in PET values in Zones 2 and 5, the slight change in Zone 3, and the wide range of ΔPET in Zones 2 and 5 as a result of the integrated interventions.

To understand more deeply the mechanisms of PET reduction, a zone-specific analysis of supporting microclimatic variables was performed (Table 5). Reductions in ambient T-air across all zones ranged from 2.6 °C to 4.2 °C. The data reveals that the most substantial attenuations in PET were consistently coupled with the largest decreases in MRT, notably in Zones 5 and 2, which recorded MRT reductions of 20.2 °C and 11.3 °C, respectively. This indicates that the mitigation of radiant heat exposure, mainly achieved through strategic shading and vegetative interventions, was a major contributor to the observed improvement in outdoor thermal comfort.

Furthermore, a significant increase in RH was observed across all zones, ranging from 12.9% to 17.2%. This increase is attributable to two synergistic factors: first, the fundamental inverse relationship between T-air and RH, where RH rises as T-air decreases due to the reduced moisture-holding capacity of cooler air (Givoni 1998); and second, the added moisture through evapotranspiration from the introduced vegetation (Alghannam and Al-Qahtani 2012[GG3.1][NA3.2]).

While changes in WS were statistically significant, their magnitude remained minor, suggesting a secondary influence on the observed thermal improvements. Overall, the analysis suggests that the proposed urban interventions contributed to shifting the microclimatic conditions toward a more thermally comfortable state, primarily through the reduction of radiant heat loads.

3.4. Statistical Significance of Thermal Improvements

Although descriptive statistics and boxplot analyses provide valuable insight into spatial thermal variations, statistical testing was required to determine whether the observed PET reductions were statistically significant. Therefore, paired-sample t-tests were conducted to compare PET values between baseline and improved scenarios within each thermal zone at 14:00.

As presented in Table 6, all thermal zones exhibited statistically significant PET reductions ($p < 0.05$) following intervention. The strongest statistical significance was observed in Zone 5 ($p < 1e\text{-}166$), followed by Zones 4 and

Zone	Δ Air Temp.	Δ PET	Δ MRT	Δ RH (%)	Δ Wind Speed
1	∇2.82°C	∇ 1.60	∇ 2.30	Δ 13.7%	Δ +0.56 m/s
2	∇ 3.94°C	∇ 7.18	∇ 11.3	Δ 16.9%	Δ +0.12 m/s
3	∇ 3.04°C	∇ 1.41	Δ +1.09	Δ 13.7%	Δ +0.009 m/s
4	∇ 2.62°C	∇ 4.50	∇ 6.84	Δ 12.9%	∇ –0.02 m/s
5	∇4.22°C	∇ 10.7	∇ 20.2	Δ 17.2%	Δ +0.135 m/s

Note: ∇ = Decrease (desired improvement); Δ = Increase (potentially positive or negative depending on context)

Table 5. Zone-specific changes (Δ) in microclimatic indicators between baseline and improved scenarios at 14:00.

Zone	P-value	Significant
1	1.22754 E-13	Yes
2	2.85257 E-48	Yes
3	1.11547 E-08	Yes
4	2.46437 E-76	Yes
5	5.4278 E-167	Yes

Table 6. Results of paired t-tests comparing PET before and after interventions in each thermal zone.

Indicator	Mean Before	Mean After	Δ (Change)	t-statistic	p-value
Air Temperature (°C)	31.37	28.03	–3.34	84.45	< 0.001
PET (°C)	46.60	40.84	–5.76	38.80	< 0.001
MRT (°C)	64.12	54.89	–9.23	28.48	< 0.001
Relative Humidity (%)	29.06	43.90	+14.84	–151.30	< 0.001
Wind Speed (m/s)	1.36	1.28	–0.08	7.04	< 0.001
Solar Radiation (W/m²)	1261.48	925.68	–335.80	26.91	< 0.001

Table 7. Paired-sample t-test results comparing base and improved scenarios for key climatic indicators.

2, corresponding to the zones that received the most comprehensive intervention strategies and achieved the largest PET reductions. In contrast, Zone 3, which received material-based intervention only, recorded the smallest PET reduction; however, the improvement remained statistically significant ($p < 1e-8$), indicating that even limited interventions produced measurable thermal effects.

Collectively, these findings indicate statistically significant simulated improvements in outdoor thermal comfort across all thermal zones.

3.5. Overall Statistical Comparison Between Baseline and Improved Scenarios

To further evaluate the overall microclimatic impact of the proposed mitigation strategies across the entire study area, paired sample t-tests were additionally conducted for six key climatic indicators: T-air, PET, MRT, RH, WS, and SR. The paired t-test approach was adopted because the same spatial grid cells were compared before and after intervention, resulting in naturally paired observations. Similar statistical approaches have been used in microclimate and ENVI-met studies to evaluate the robustness of intervention outcomes (Taleghani et al. 2016; Zölch et al. 2019). As shown in Table 7, the results illustrate statistically significant differences ($p < 0.001$) across all variables, confirming that the observed changes are attributable to the mitigation strategies applied rather than random variation.

The results presented a significant microclimatic improvement after intervention. T-air decreased by 3.34 °C ($t = 84.45$), while PET decreased by 5.76 °C, from 46.60°C to 40.84°C ($t = 38.80$), indicating a considerable simulated improvement in outdoor thermal comfort conditions. MRT showed a notable reduction of 9.23 °C, highlighting the effectiveness of shading and reflective surface strategies in reducing radiant heat exposure. These results are aligned with previous findings that PET is highly sensitive to radiant heat load (Lin et al. 2010a; Matzarakis et al. 1999). RH increased by approximately 15%, supporting evaporative cooling effects and improved thermal perception, which is consistent with studies in arid climates that identified humidity gain as a critical factor for mitigating heat stress (Shashua-Bar et al. 2011). WS showed a statistically significant but practically negligible reduction (–0.08 m/s, $t = 7.04$), likely due to increased vegetation and surface roughness. However, its influence on overall thermal comfort remained limited compared to other variables, likely due to the dominant influence of radiant heat and shading conditions within the studied hot-arid urban morphology. Finally, SR also decreased significantly by 335.8 W/m², confirming the important role of shading interventions and surface modifications in mitigating thermal stress. Overall, the statistical analysis indicates the potential effectiveness of the proposed interventions in improving outdoor microclimatic conditions within the simulated study area.

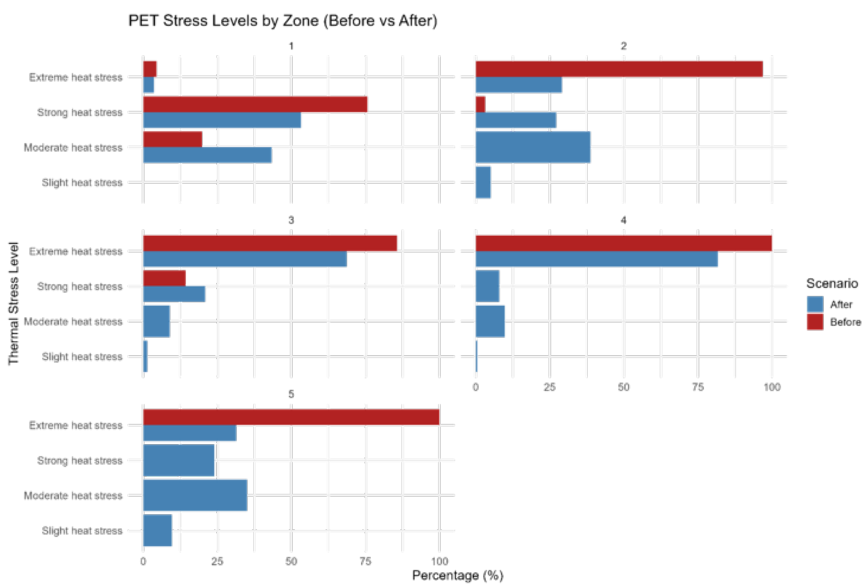


Figure 14. Distribution of PET stress levels across thermal zones before and after intervention.

3.6. PET Stress Levels Classification

To complement the quantitative analysis of PET values and their spatial distributions, PET results were classified into thermal stress categories to facilitate interpretation of outdoor thermal comfort conditions across the study area. The classification adopted four thermal stress categories: slight, moderate, strong, and extreme heat stress, based on the widely applied PET thermal perception scale developed by Matzarakis and Mayer (1996) and subsequently adopted in outdoor thermal comfort studies (Lin et al. 2010a; Lin et al. 2010b).

Figure 14 illustrates the distribution of PET thermal stress levels across the five thermal zones in both baseline and improved scenarios. After intervention, clear shifts from higher to lower thermal stress categories were observed in most zones. Zone 5 presented one of the most notable improvements, with the proportion of areas classified as extreme heat stress decreasing from 100% to 31.3%, accompanied by considerable increases in moderate and slight heat stress categories. Similarly, Zone 2 recorded a reduction in extreme heat stress from 96.8% to 29.0%, indicating substantial thermal improvement after vegetation, shading, and surface modification interventions. In contrast, Zone 4 continued to be exposed mainly to extreme thermal stress conditions after intervention, with 81.8% of the zone remaining within the extreme heat stress category, reflecting the relatively limited effectiveness of the interventions applied in this highly exposed paved area. Zones 1 and 3 presented relatively less improvement, mainly characterized by partial shifts from high toward moderate heat stress levels.

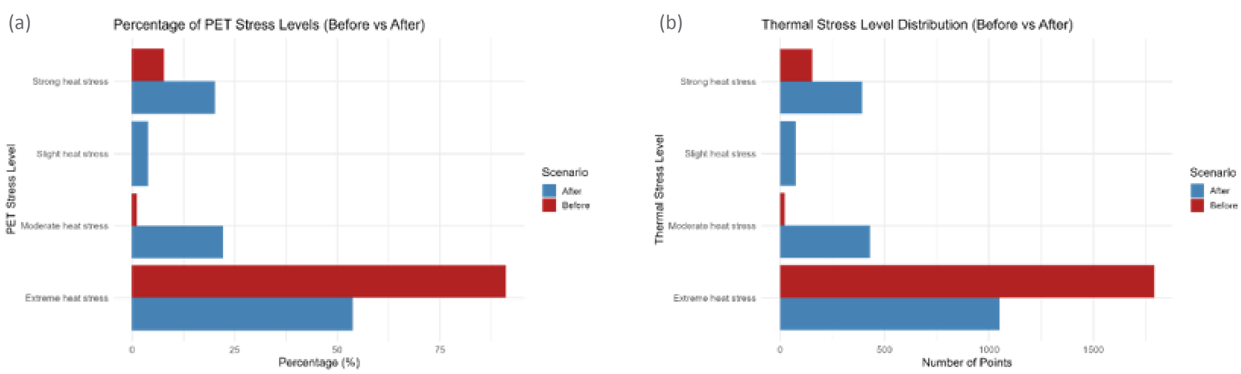


Figure 15. PET stress levels across the study area: a – Percentage distribution before vs. after the intervention; b – Absolute count of pixels per PET stress level before and after the intervention.

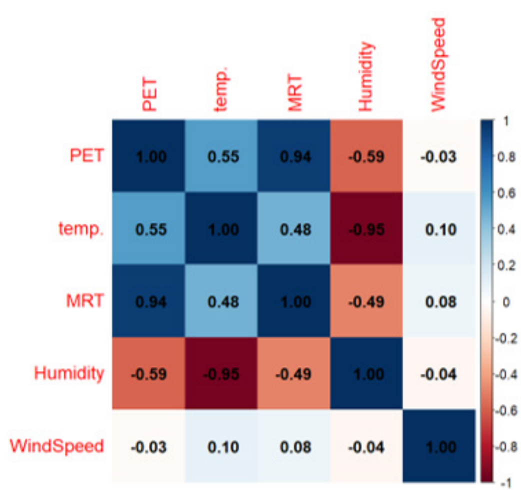


Figure 16. Correlation matrix between PET and key microclimatic variables.

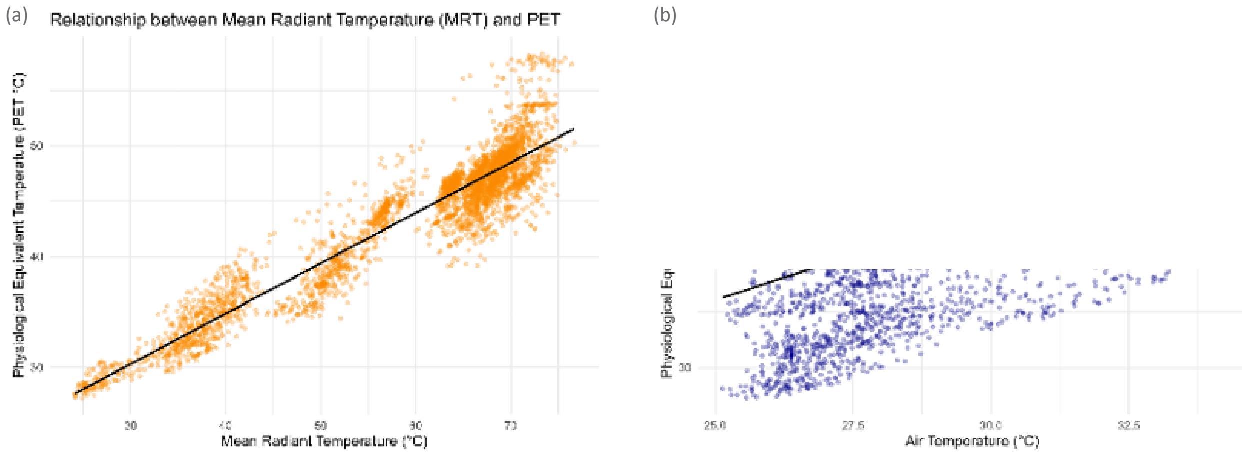


Figure 17. Scatterplot analysis of PET relationships: a – PET–MRT; b – PET–T-air.

To evaluate the overall thermal improvement across the entire study area, Figure 15 presents both the percentage distribution and absolute frequency of PET thermal stress categories before and after intervention. Under baseline conditions, extreme heat stress dominated approximately 90% of the study area, corresponding to 1,790 spatial grid cells. After intervention, this percentage decreased significantly to 41.4% (1,048 grid cells). At the same time, areas classified as moderate heat stress increased significantly from 22 to 431 grid cells, while 75 grid cells shifted into the slight heat stress category, which was almost non-existent under baseline conditions. These results indicate a comprehensive overall transition toward improved outdoor thermal comfort conditions across the site.

Overall, PET stress level classification confirms that the proposed mitigation strategies have achieved significant improvements in outdoor thermal comfort conditions. While Zones 2 and 5, which received multiple combined interventions, achieved the most notable reductions in thermal stress, other zones showed more moderate improvements depending on the type and extent of intervention applied. The emergence of slight and moderate thermal stress categories in areas previously dominated by extreme heat stress demonstrates the potential effectiveness of the combined climate-responsive interventions in reducing extreme outdoor thermal discomfort within hot-arid urban environments.

3.7. Correlation Between PET and Climatic Indicators

To further investigate the microclimatic factors influencing outdoor thermal comfort within the study area, correlation analysis was conducted between PET and key climatic variables, including T-air, MRT, RH, and WS. As illustrated in Figure 16, the correlation matrix revealed a very strong positive correlation between PET and MRT (r = 0.94), indicating the dominant influence of radiant heat exposure on perceived thermal stress. T-air also exhibited a moderate positive correlation with PET (r = 0.55). In contrast, RH showed a moderate negative correlation (r = −0.59), whereas WS demonstrated only a negligible relationship with PET (r = −0.03).

These relationships were further examined through scatterplot analysis. Figure 17a demonstrates a strong linear relationship between PET and MRT, which is expected given the substantial contribution of radiant heat conditions to PET calculations. Figure 17b shows a relatively weaker, though still positive, relationship between PET and T-air, characterized by greater data dispersion.

Overall, the findings indicate that reducing MRT through shading strategies, vegetation, and reflective surface materials represents the most effective approach for improving outdoor thermal comfort within the study area. The limited influence of WS suggests that convective cooling played a secondary role in the hot-arid climatic and spatial conditions of the study area.

3.8. Summary of Key Findings

The results collectively demonstrate that the proposed climate-responsive interventions achieved significant improvements in outdoor thermal comfort across the study area. Spatial PET distributions, heatmaps, boxplot analyses, statistical testing, and zone-based comparisons consistently revealed reductions in thermal stress after intervention. PET, which was adopted as the main thermal comfort indicator, decreased across all thermal zones, with the greatest reductions observed in Zones 2 and 5, where multiple combined mitigation interventions were applied. These thermal improvements were associated with reductions in MRT and T-air, along with increases in RH. Correlation analysis also confirmed the dominant effect of MRT on PET variation, emphasizing the critical role of shading and radiant heat control in improving thermal comfort within hot-arid urban environments.

Statistical analyses demonstrated that the observed changes in all major climatic indicators were highly statistically significant ($p < 0.001$), indicating the potential effectiveness of the proposed mitigation strategies within the simulated study conditions. In addition, PET stress level classification revealed a significant shift from extreme heat stress toward more moderate and thermally tolerant conditions, particularly in areas receiving combined interventions of vegetation, shading, and surface materials. Nevertheless, spatial variation in intervention performance remained evident. Certain zones, particularly Zone 4, continued to experience high thermal stress despite intervention, indicating the limitations of the limited intervention configurations applied within highly exposed urban spaces. Overall, these findings provide a strong analytical foundation for the subsequent discussion of climate-responsive urban design strategies in hot-arid environments.

4. DISCUSSION

This study investigated the potential effectiveness of the combined climate-responsive interventions in improving outdoor thermal comfort within the Governmental District of Egypt's New Administrative Capital, representing a hot-arid urban context characterized by intense solar exposure and a lack of natural shading. The simulation results demonstrated consistent reductions in PET across all identified thermal zones after the intervention were applied, although the magnitude of improvement varied spatially depending on the urban form, shading conditions, and intervention type. Areas characterized by higher solar exposure, limited existing shading, and extensive hardscape surfaces generally demonstrated greater sensitivity to climate-responsive interventions.

The greatest improvements were observed in Zones 2 and 5, where PET decreased by 7.18 °C and 10.72 °C, respectively. These zones received integrated intervention strategies, including increased vegetation coverage, shading structures, localized urban form modifications, reflective surface materials, and water features. The strong thermal response observed in these two areas suggests that combining multiple mitigation strategies can contribute to significant reductions in outdoor heat stress in large exposed urban spaces. The simultaneous reduction in MRT and PET within these zones further reflects the strong contribution of radiative heat conditions to PET variation under hot-arid climatic conditions. In contrast, Zones 1 and 3 showed relatively limited thermal improvement. Zone 1 already benefited from significant shading caused by buildings under basic conditions and therefore did not require any major intervention. The relatively slight PET reduction observed in this zone reflects the pre-existing favorable microclimatic conditions rather than poor intervention performance. Zone 3 relied mainly on modifying surface materials by replacing asphalt with light-colored concrete. Although this strategy achieved measurable thermal benefits, the reduction in PET remained limited compared with zones receiving multiple combined interventions within the present study. This finding suggests that surface reflectivity alone may be insufficient to significantly mitigate thermal stress in highly exposed urban environments without additional shading or vegetation measures. Zone 4 continued to experience relatively high thermal stress even after the interventions were applied. Despite the installation of wooden shading structures, the effectiveness of mitigation remained limited due to the extensive use of granite and marble paving surfaces, limited vegetation opportunities, and the functional and formal characteristics associated with government entrance plazas. This finding highlights the importance of considering site-specific spatial and functional constraints when applying climate-responsive interventions in formal urban spaces.

Correlation analysis demonstrated that MRT was the climatic parameter most strongly associated with PET ($r = 0.94$), while T-air showed a moderate positive relationship and WS displayed only limited influence. These findings are consistent with previous studies conducted in hot-arid climates, which emphasize that reducing radiative heat exposure through shading and surface treatment is generally more effective than relying solely on ventilation enhancement (Coccolo et al. 2016; Salata et al. 2017; Taleghani et al. 2018). The strong dependence of PET on MRT also explains why zones receiving shading and vegetation interventions achieved much greater thermal improvements than those relying only on material modifications.

The PET stress classification analysis additionally demonstrated a marked shift from extreme thermal stress toward moderate and slight heat stress categories after intervention implementation. The emergence of moderate thermal stress conditions in areas previously dominated by extreme heat stress indicates not only numerical thermal improvement but also enhanced human thermal perception and outdoor usability. However, despite these improvements, several areas remained within strong or extreme thermal stress categories during peak afternoon conditions, reflecting the intensity of summer heat exposure in hot-arid urban environments.

Although the findings suggest the potential effectiveness of the combined mitigation measures applied in the present study, the results should be interpreted within the methodological scope of the simulation framework. While certain zones received different dominant intervention types, the study did not conduct fully controlled, independent simulations for each mitigation strategy under identical spatial and microclimatic conditions. Therefore, the study cannot quantitatively isolate the individual contribution of each intervention type. Instead, the results primarily demonstrate the collective simulated performance of the applied climate-responsive intervention configurations within different thermal zones.

This study has several limitations. First, the simulation analysis was conducted for one typical summer day and focused primarily on the 14:00 period, corresponding to representative peak daytime thermal stress conditions. The selected simulation period was characterized by high SR exposure and elevated daytime air temperatures, representing critical summer outdoor thermal stress conditions within the study area. Although this approach enables evaluation under critical thermal exposure conditions, it does not capture daily or seasonal thermal variation throughout the year. Second, the study was limited to a single case study area within Egypt's New Administrative Capital, which may limit the direct generalizability of the findings to other urban contexts or climatic regions without further comparative investigation. In addition, the study relied exclusively on ENVI-met simulation outputs without field measurements or empirical validation. While ENVI-met is widely applied in urban microclimate research and has been validated in previous studies, the absence of on-site observational data limits direct assessment of actual thermal performance. Furthermore, the improved scenario examined a combined multi-intervention strategy rather than evaluating the isolated effects of individual mitigation measures separately. Finally, this study did not address practical implementation aspects, such as long-term vegetation maintenance, irrigation needs, water consumption, economic feasibility, and seasonal operational performance. Future research may address these limitations through multi-season simulations, field validation campaigns, comparative analysis of individual strategies, and by evaluating long-term performance under real urban operating conditions.

Despite these limitations, the study provides important practical implications for climate-responsive urban planning in Egypt and similar hot-arid regions. The findings suggest that prioritizing SR control through integrated shading, vegetation, and surface modification strategies can significantly improve outdoor thermal comfort in large-scale urban developments. However, implementation feasibility should also consider long-term maintenance requirements, irrigation needs, and water resource availability, particularly in arid climates where vegetation and water-based cooling strategies may involve additional environmental and operational costs.

Overall, the study demonstrates that integrated urban climate mitigation strategies can contribute to significant reductions in outdoor thermal stress when adapted to localized spatial and morphological conditions. The findings contribute to the growing body of research supporting climate-sensitive urban design approaches for enhancing thermal resilience and outdoor livability in rapidly growing cities with hot and dry climates.

5. CONCLUSION AND RECOMMENDATIONS

This study examined the potential thermal performance of integrated climate-responsive urban design interventions within the Governmental District of Egypt's New Administrative Capital, which represents a hot-arid urban environment characterized by high solar exposure and limited outdoor thermal comfort during summer conditions. By combining ENVI-met simulations with spatial analysis and statistical evaluation using programming, the study examined the impact of integrated mitigation strategies on outdoor microclimatic conditions and human thermal comfort.

The simulation results showed measurable thermal improvements across all identified thermal zones following intervention implementation. T-air reductions ranged from approximately 2.6 °C to 4.2 °C, while PET reductions ranged between 1.4 °C and 10.7 °C depending on local spatial characteristics and intervention type. The largest reductions in PET were observed in Zones 2 and 5 (-7.18 °C and -10.7 °C respectively), where combined interventions including vegetation, shading structures, surface material modification, localized urban form adjustments, and water features were applied. MRT also decreased significantly, reaching reductions of up to 20.2 °C, highlighting the strong influence of radiative heat conditions on outdoor thermal comfort variation in hot-arid climates.

The PET stress classification analysis revealed a marked shift from extreme thermal stress toward more moderate thermal perception categories after intervention implementation. However, spatial variation in thermal performance remained evident. Some areas, particularly Zone 4, continued to be exposed to relatively high levels of heat stress due to functional, spatial, and morphological constraints that limited the applicability of comprehensive mitigation measures. In contrast, zones characterized by greater opportunities for vegetation integration, shading provision, and localized urban form modification demonstrated more substantial thermal improvement. These findings highlight the importance of adapting climate-responsive interventions to local urban conditions rather than applying standardized strategies across all urban spaces. Correlation analysis confirmed that MRT is the climatic parameter most associated with PET, emphasizing the importance of shading, SR control, and surface treatment in improving outdoor thermal comfort. The results also indicate that zones receiving multiple combined interventions generally exhibited greater thermal improvements than zones characterized by limited intervention applications under the specific conditions examined in this study. However, the study was limited to evaluating only a single integrated intervention scenario; therefore, it was not possible to determine the individual contribution of each mitigation strategy.

The study contributes to the growing body of research on outdoor thermal comfort in hot-arid cities by integrating systematic literature review findings with simulation-based microclimatic assessment and zone-based intervention analysis. The proposed analytical framework demonstrates how thermal zoning and localized climate-responsive strategies can support more context-sensitive urban heat mitigation in large-scale governmental developments and similar hot-arid urban environments. The results support the integration of vegetation, shading systems, reflective materials, and localized urban form modifications as part of comprehensive urban heat mitigation strategies. Several limitations should be acknowledged, and the findings should therefore be interpreted as simulation-based performance indications rather than direct representations of real-world thermal behavior. The analysis was based on a simulation of one typical summer day, with detailed evaluation focused on representative peak daytime thermal stress conditions at 14:00. In addition, the study relied on ENVI-met simulations without field measurements for validation. Therefore, future research should include long-term temporal analysis, seasonal comparisons, field-based validation measurements, and comparative tests of individual mitigation strategies to better determine their relative effectiveness and applicability under different urban and climatic conditions. Overall, the study indicates the potential of integrated climate-responsive urban design approaches to improve outdoor thermal comfort and reduce heat stress in hot-arid urban environments, while highlighting the importance of site-specific and context-sensitive intervention planning for achieving sustainable urban thermal resilience.

6. POLICY AND ENVIRONMENTAL IMPLICATIONS

The findings provide useful simulation-based insights for sustainable urban design and policy development in Egypt and other MENA cities with comparable hot-arid climatic conditions. Integrating outdoor thermal comfort considerations into urban planning frameworks may contribute to improving urban liveability and climate resilience in rapidly developing environments. In practice, urban designers and planners should prioritize strategies that reduce radiant heat exposure through distributed shading elements, high-albedo pavements, and strategically located vegetation that provides both shading and evaporative cooling benefits.

At the policy level, local authorities and decision-makers are encouraged to institutionalize climate-responsive urban design principles by incorporating thermal comfort assessment tools within planning policies, urban design guidelines, and building regulations. Such integration may help ensure that environmental quality and public health considerations are addressed during the early stages of urban development rather than through post-construction retrofitting approaches (UN-Habitat 2015).

Nevertheless, the applicability of these recommendations may vary depending on local urban morphology, climatic conditions, implementation feasibility, water resource availability, and long-term maintenance requirements. Therefore, climate-responsive interventions should be adapted to the specific environmental and spatial characteristics of each urban context rather than applied uniformly across different urban settings.

Furthermore, future research should focus on validating simulation outputs through on-site field measurements and user perception surveys to capture real-time thermal experiences and behavioural responses. Additionally, employing complementary simulation platforms such as DesignBuilder and Ladybug Tools may support comparative analyses and multi-scalar evaluation of urban thermal performance. Extending future investigations to include seasonal variability, long-term operational assessment, and the independent evaluation of individual mitigation strategies would further strengthen the understanding of outdoor thermal comfort dynamics and support evidence-based climate-responsive urban design in hot-arid regions.

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DISCLOSURE STATEMENT

The authors declare that they have no conflicts of interest regarding the publication of this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study, including ENVI-met simulation results (T-air, RH, WS, MRT, and PET) and statistical analysis generated in R, have been provided as supplementary material with this submission. Additional data is available from the corresponding author upon reasonable request.

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Appendix

Appendix A – Figures

Fig. 3: VOS viewer keyword co-occurrence map of the selected literature, illustrating keyword frequency, co-occurrence relationships, and thematic clustering within outdoor thermal comfort research.

Fig. 7: Methodological framework.

Fig. 8: Multi-scale spatial context of the selected case study area.

Fig. 9: Google Maps images of the study area illustrating the existing landscape conditions.

Fig. 10: Spatial distribution of the five thermal zones identified through K-means clustering based on six baseline microclimatic variables.

Fig. 11a: R-based heatmaps of PET spatial distribution at 14:00 - baseline scenario.

Fig. 11b: R-based heatmaps of PET spatial distribution at 14:00 - improved scenario.

Fig. 12: Spatial distribution of PET reduction (ΔPET = Baseline – Improved) across the study area following mitigation interventions.

Fig. 13a: Boxplot of PET values before and after interventions.

Fig. 13b: Boxplot of Delta PET (Mean and Median).

Fig. 14: Distribution of PET stress levels across thermal zones before and after intervention.

Fig. 15 a: PET stress levels across the study area – Percentage distribution before vs. after the intervention.

Fig. 15 b: PET stress levels across the study area – Absolute count of pixels per PET stress level before and after the intervention.

Fig. 16: Correlation matrix between PET and key microclimatic variables.

Fig. 17a: Scatter plot of PET vs MRT.

Fig. 17b: Scatter plot of PET vs T_air.

Fig. 1 in Table 2: Model Domain for the Study Area (base case).

Fig. 2 in Table 2: Model Domain for the Study Area (after intervention).

Appendix B – Datasets (Excel Files)

PRISMA_611_Studies.xlsx → Comprehensive list of the 611 studies initially retrieved and screened.

VOSviewer_Keyword_Mapping_Data.xlsx → Bibliometric keyword mapping dataset used for network analysis.

Final_Selected_Studies_30.xlsx → Dataset of the final 30 studies selected for in-depth review.

Pixel_Data_Baseline.xlsx → Pixel-level microclimatic data for the baseline scenario.

Pixel_Data_After_Intervention.xlsx → Pixel-level microclimatic data after the design interventions.

Stats_PET_per_Zone.xlsx → PET statistical values extracted for each thermal zone.

Zone_PET_Stress_Percentages.xlsx → Distribution of PET stress percentages across zones.

PET_Thermal_Stress_Levels.xlsx → Categorization of PET values into thermal stress levels.

Notations

CFD – Computational Fluid Dynamics

ENVI-met – Environmental Meteorology Model (simulation tool)

LAI – Leaf Area Index

MRT – Mean Radiant Temperature

NAC – New Administrative Capital

PET – Physiological Equivalent Temperature

PRISMA – Preferred Reporting Items for Systematic Reviews and Meta-Analyses

RH – Relative Humidity

SDG – Sustainable Development Goals

SVF – Sky View Factor

T-air – Air temperature

THI – Temperature–Humidity Index

UHI – Urban Heat Island

UTCI – Universal Thermal Climate Index

VOS-viewer – Visualization of Similarities Viewer (software for bibliometric mapping)

WOS – Web of Science database

WS – Wind speed