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Advanced Civil Infrastructure Strategies for Urban Heat Mitigation: Multiscale Evaluation of Pavement Thermal Behaviour, Structural Shading Geometry, and Landscape Cooling Dynamics in Zabeel Park, Dubai

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ABSTRACT

Rapid urbanization in arid regions has intensified the Urban Heat Island (UHI) effect, adversely affecting outdoor thermal comfort, public health, and the long-term performance of civil infrastructure. In desert megacities such as Dubai, conventional heat mitigation measures are often implemented in isolation, limiting their effectiveness under extreme climatic conditions. This study presents an integrated civil infrastructure framework for urban heat mitigation through a multiscale evaluation of pavement thermal behaviour, structural shading geometry, and landscape cooling dynamics, using Zabeel Park, Dubai, as a representative case study. The proposed methodology adopts a multiscale assessment approach encompassing material-level, human-scale, and park-scale analyses. Pavement thermal behaviour is evaluated by examining surface temperature variations, heat storage characteristics, and radiative properties under both shaded and unshaded conditions. Structural shading strategies are analysed through geometric assessment of canopy configurations, shadow coverage ratios, and temporal shading performance based on solar path characteristics specific to Dubai's latitude. Landscape cooling dynamics are investigated by assessing vegetation distribution, evapotranspiration potential, and the synergistic interaction between shaded pavements and planted areas in reducing near-surface air temperatures. The results indicate that integrated heat mitigation strategies significantly outperform standalone interventions. Shaded pavements demonstrate substantial reductions in peak surface temperatures compared to fully exposed surfaces, while optimised shading geometries improve the duration and spatial continuity of thermal relief along pedestrian corridors. Vegetated zones further enhance cooling performance through evaporative processes, particularly when combined with shading structures that reduce direct solar radiation on pavement materials. Notably, the findings reveal nonlinear synergistic effects, where the combined application of material selection, geometric shading design, and landscape configuration produces greater thermal benefits than the cumulative impact of individual measures. This study contributes a design-oriented and evidence-based framework for civil engineers and urban planners aimed at improving outdoor thermal comfort and climate resilience in arid urban environments. By demonstrating the effectiveness of integrating pavement materials, shading geometry, and landscape

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systems within a unified infrastructure strategy, the research offers practical guidance for heat-resilient park and pedestrian space design. The proposed framework is transferable to other hot-climate cities and supports sustainable urban infrastructure planning under increasing thermal stress.

Keywords: Urban Heat Island Mitigation; Pavement Thermal Behaviour; Structural Shading Geometry; Landscape Cooling Dynamics; Outdoor Thermal Comfort; Heat-Resilient Civil Infrastructure; Arid Urban Environments; Sustainable Urban Design; Zabeel Park, Dubai.

Introduction:

Rapid urbanization, combined with accelerating climate change, has significantly intensified the Urban Heat Island (UHI) effect across cities worldwide. The replacement of natural land covers with impervious surfaces, high-density built environments, and thermally absorptive construction materials has resulted in elevated surface and ambient air temperatures in urban areas relative to their rural surroundings. These thermal anomalies impose considerable burdens on public health, outdoor thermal comfort, energy consumption, and the durability of civil infrastructure. In hot and arid regions, where baseline climatic conditions already approach or exceed human comfort thresholds, the consequences of UHI amplification are particularly severe [1]. Arid megacities such as Dubai experience extreme solar radiation, prolonged heatwaves, and limited natural vegetation, creating a challenging environment for sustainable urban development. Summer air temperatures frequently exceed 45 °C, while surface temperatures of exposed pavements can rise substantially higher, posing risks to pedestrians and increasing radiative heat loads within urban canyons and open spaces. Under such conditions, public parks and pedestrian-oriented spaces play a critical role as potential thermal refuges; however, their effectiveness depends strongly on the interaction of pavement materials, structural shading systems, and landscape configurations. The performance of these spaces cannot be adequately understood through single-factor analyses, necessitating integrated and context-specific evaluations [2]. Urban heat mitigation research has expanded considerably over the past two decades, with substantial attention devoted to individual strategies such as cool pavements, shading devices, and urban greening. Pavement-focused studies have demonstrated that conventional asphalt and concrete surfaces possess high thermal mass and low reflectivity, contributing to heat storage and delayed nocturnal cooling. High-albedo and modified pavement materials have been proposed to reduce surface temperatures; however, their performance in arid climates is often constrained by glare, aging, and limited effectiveness under intense solar exposure. Similarly, structural shading systems such as pergolas, canopies, and architectural overhangs have been shown to reduce direct solar radiation and improve pedestrian thermal comfort, yet their effectiveness is highly dependent on geometric configuration, orientation, and temporal alignment with solar trajectories [3]. Landscape-based cooling strategies, particularly vegetation and water features, are widely recognized for their potential to reduce urban temperatures through shading and evapotranspiration. In arid environments, however, the cooling benefits of vegetation must be balanced against water scarcity, irrigation

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demands, and maintenance requirements. Recent studies suggest that vegetation alone may offer limited thermal relief when deployed without complementary shading or material strategies, as exposed pavements continue to act as dominant heat sources. Despite this growing body of knowledge, most existing studies address these mitigation measures independently, offering fragmented insights that are difficult to translate into integrated civil infrastructure design. In reality, urban thermal environments are shaped by complex and nonlinear interactions among surface materials, shading geometry, and landscape systems [4]. Pavement thermal behaviour is not solely governed by material properties but is strongly influenced by shading patterns imposed by structures and trees. Likewise, the effectiveness of shading devices depends on the thermal characteristics of the surfaces they protect, while vegetation performance is enhanced when evapotranspiration occurs over cooler, shaded substrates. The lack of multiscale, integrated assessments limits the ability of civil engineers and urban planners to optimize outdoor environments, particularly in extreme climates where resource efficiency and thermal resilience are paramount. Zabeel Park in Dubai provides an ideal living laboratory for investigating these interactions. As a major urban park embedded within a dense metropolitan context, it features diverse pavement materials, a range of structural shading geometries, and varied landscape typologies. The park's exposure to intense solar radiation, high pedestrian activity, and arid climatic conditions makes it highly representative of public open spaces in Gulf cities [5]. Despite its relevance, comprehensive studies examining the coupled thermal effects of pavements, shading structures, and landscape elements within such parks remain scarce. To clarify the positioning of this study within the existing literature, Table 1 summarizes key urban heat mitigation strategies, their typical evaluation focus, and identified research gaps in arid urban contexts.

Table 1: Urban Heat Mitigation Strategies and Research Gaps in Arid Environments

Strategy Category	Primary Focus in Existing Studies	Typical Scale of Analysis	Key Limitations	Research Gap Addressed in This Study
Pavement materials	Albedo, thermal mass, surface temperature	Material / surface scale	Limited consideration of shading and landscape interactions	Coupled evaluation of pavement thermal behaviour under shading and vegetation
Structural shading	Solar radiation reduction, shadow coverage	Human / pedestrian scale	Geometry often assessed without material thermal response	Integration of shading geometry with pavement heat storage effects

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Landscape cooling	Evapotranspiration, vegetation density	Park / neighborhood scale	High water demand; limited synergy analysis	Assessment of landscape cooling combined with shaded pavements
Integrated strategies	Rarely addressed comprehensively	Fragmented or conceptual	Lack of multiscale, empirical frameworks	Multiscale, evidence-based integration in an arid park setting

Against this backdrop, the present study advances the field by proposing an integrated civil infrastructure framework that simultaneously evaluates pavement thermal behaviour, structural shading geometry, and landscape cooling dynamics at multiple spatial scales. The research moves beyond isolated performance metrics by examining how material properties, geometric design, and ecological processes interact to shape outdoor thermal conditions [6]. By adopting a multiscale perspective encompassing material-level thermal responses, human-scale pedestrian comfort, and park-scale cooling patterns, the study captures synergistic and nonlinear effects that are often overlooked in conventional analyses. The specific objectives of this research are to: (i) quantify pavement thermal responses under varying exposure and shading conditions in an arid park environment; (ii) evaluate the effectiveness of different structural shading geometries in providing spatially and temporally consistent thermal relief; and (iii) assess the role of landscape elements in enhancing cooling performance and moderating pavement heat accumulation [7]. Through these objectives, the study aims to generate design-oriented insights that support the development of heat-resilient urban parks and pedestrian spaces in desert cities. By focusing on Zabeel Park, Dubai, this research contributes empirically grounded and transferable knowledge for civil infrastructure planning in hot-climate regions. The proposed framework offers a practical foundation for integrating material selection, geometric design, and landscape strategies into cohesive urban heat mitigation solutions, supporting sustainable and human-centred urban development under escalating thermal stress.

Structural Shading Geometry:

Structural shading geometry constitutes a fundamental component of urban heat mitigation in outdoor environments, particularly in arid cities where direct solar radiation is the dominant contributor to surface and ambient temperature elevation. Unlike material-based interventions that primarily influence heat absorption and storage, shading structures act as first-order modifiers of the urban radiation balance by intercepting incoming shortwave solar energy before it reaches pavements, pedestrians, and surrounding landscape elements. The thermal effectiveness of shading is therefore intrinsically linked to geometric configuration, orientation,

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height, spacing, and temporal alignment with local solar trajectories [8]. In extreme climates such as Dubai's, even minor geometric inefficiencies can result in substantial reductions in shading performance during critical peak heat periods. In practice, shading systems implemented in urban parks and pedestrian corridors can be broadly categorized as fixed or parametric, each exhibiting distinct geometric characteristics and thermal implications. Fixed shading systems, including conventional pergolas, tensile canopies, colonnades, and architectural overhangs, employ static geometries that remain unchanged throughout the day and across seasons. These systems are commonly adopted in civil infrastructure projects due to their structural simplicity, ease of construction, and low operational requirements [9]. However, fixed shading geometries are often designed based on simplified assumptions of average solar angles or architectural aesthetics, rather than detailed solar-path analysis. As a result, while such structures may provide visually apparent shade, their thermal effectiveness is frequently limited to specific times of day, leaving pedestrian pathways and pavement surfaces exposed during midday and early afternoon hours when thermal stress is most severe. Parametric shading systems represent an evolution in shading design, leveraging computational geometry and climate-responsive principles to optimize form in relation to solar altitude, azimuth, and spatial use patterns [10]. These systems may incorporate inclined or curved surfaces, modular panels, perforated elements, or louvered configurations designed to maximize shadow coverage during peak solar exposure. In arid urban contexts, parametric shading has demonstrated superior performance in extending shadow duration and maintaining spatial continuity of shaded zones, thereby enhancing both pavement cooling and pedestrian comfort. Nevertheless, the application of parametric shading in large-scale civil infrastructure remains limited, largely due to increased design complexity, higher initial costs, and insufficient integration between civil engineering and architectural design workflows. The interaction between shading geometry and solar path is a decisive factor governing thermal performance. Solar altitude and azimuth vary continuously throughout the day and season, directly influencing shadow length, orientation, and persistence. In low-latitude desert cities such as Dubai, high summer solar altitudes produce short but intense shadows around midday, while longer shadows occur during morning and late afternoon hours [11]. Shading structures that are not explicitly designed to account for these dynamics may provide inadequate protection during periods of maximum thermal load. Moreover, shadow duration plays a critical role in regulating pavement thermal behaviour. Pavement surfaces exposed intermittently to solar radiation tend to reheat rapidly, diminishing cumulative cooling benefits and increasing longwave re-radiation to pedestrians. Continuous or overlapping shadow coverage, by contrast, can suppress surface heat accumulation and contribute to sustained reductions in near-surface air temperatures [12]. Within urban park environments, shading performance is further influenced by interactions between built structures and landscape elements. Tree canopies, pergolas, and architectural shading may overlap spatially, altering shadow patterns in complex ways throughout the day. When such elements are designed independently, redundancy may occur in some areas while other zones remain excessively exposed. This lack of coordination underscores a persistent integration gap between civil infrastructure planning and architectural shading design. Shading structures are

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frequently treated as secondary or aesthetic features, rather than as integral components of the thermal infrastructure system [13]. Civil engineering processes often prioritize circulation, structural safety, and constructability, while shading geometries are developed with limited consideration of pavement thermal properties, landscape cooling dynamics, or pedestrian comfort metrics. The consequences of this disciplinary disconnect are evident in many urban spaces, where shading structures fail to align with high-heat pavements or are positioned without regard to peak pedestrian usage periods. Similarly, high-performance pavements and vegetated zones may underperform thermally due to insufficient or poorly oriented shading. Addressing these shortcomings requires an integrated design approach in which shading geometry is evaluated alongside pavement materials and landscape systems using shared, performance-based criteria [14]. This integration is especially critical in arid environments, where thermal margins are narrow and design inefficiencies are amplified under extreme climatic stress. To contextualize the role of shading geometry within the broader body of urban heat mitigation research, Table 2 provides a comparative overview of fixed and parametric shading systems, their typical design focus, and key limitations in arid urban applications.

Table 2: Comparison of Structural Shading Geometry Approaches in Arid Urban Environments

Shading approach	Geometric characteristics	Typical performance focus	Limitations in arid climates	Contribution to this study
Fixed shading	Static, uniform geometry	Visual shade provision	Limited temporal adaptability; reduced midday effectiveness	Baseline shading assessment
Parametric shading	Solar-responsive, optimized geometry	Shadow duration and continuity	Higher complexity; limited implementation	Enhanced thermal performance evaluation
Hybrid shading	Combined built and vegetative forms	Partial microclimatic benefit	Lack of integrated evaluation metrics	Synergistic cooling analysis

The geometric principles governing shading–solar interaction are conceptually illustrated in Figure 1, which depicts how different shading configurations interact with solar trajectories to influence shadow patterns, pavement exposure, and pedestrian-scale thermal zones within an arid urban park setting.

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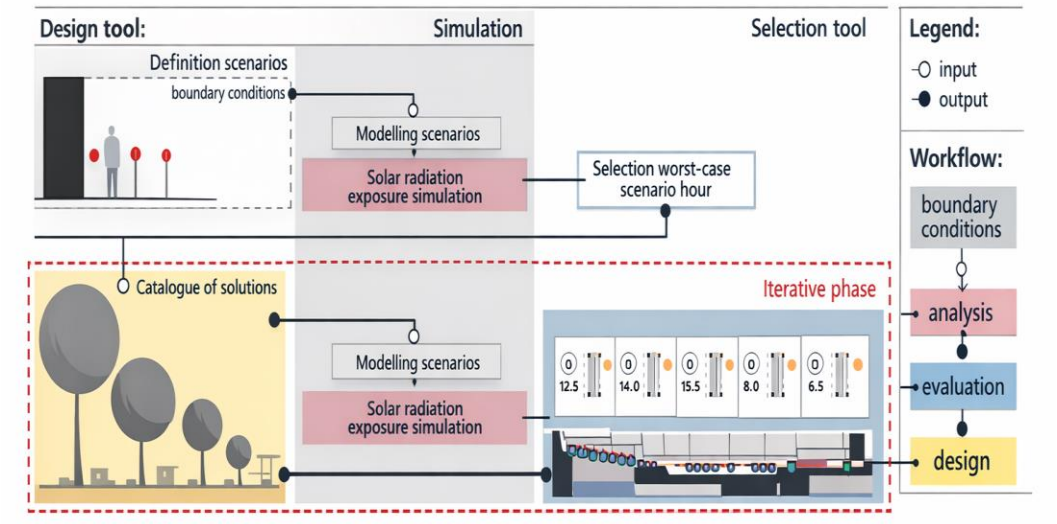


Figure 1: Structural shading geometry interacting with solar path and pedestrian-scale thermal conditions in an arid urban park.

The figure demonstrates differences in shadow length, continuity, and temporal coverage produced by fixed and parametric shading structures across morning, midday, and afternoon periods, and their influence on pavement surface temperatures and pedestrian comfort zones. Structural shading geometry represents a highly influential yet under-integrated mechanism for urban heat mitigation in arid environments. While fixed shading systems provide essential baseline protection, their static nature limits performance under extreme solar conditions. Parametric shading offers improved alignment with solar dynamics and enhanced thermal benefits but remains underutilized due to design and coordination challenges [15]. The effectiveness of both approaches is ultimately governed by solar-path interactions and the degree of integration with pavement and landscape systems. By embedding shading geometry within a unified civil infrastructure framework, urban parks and pedestrian spaces can be transformed into thermally resilient environments capable of mitigating heat stress in desert cities.

Landscape Cooling in Arid Parks:

Landscape systems constitute a critical component of urban heat mitigation in arid environments, where natural cooling mechanisms are constrained by limited water availability and extreme thermal conditions. In urban parks, vegetation and soil–plant–atmosphere interactions influence microclimatic conditions through shading, evapotranspiration, and modification of surface energy balances. Unlike built shading or pavement-based strategies, landscape cooling operates through biophysical processes that are highly sensitive to vegetation density, species selection, irrigation practices, and local climatic conditions. In desert cities such as Dubai, the effectiveness of landscape-based cooling is therefore governed by a delicate balance between thermal performance and resource efficiency [16]. Vegetation density plays a central role in determining the cooling potential of arid parks, yet it simultaneously

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drives water demand, creating a fundamental trade-off in landscape design. Dense vegetation can provide extensive shading and increased evapotranspiration, both of which contribute to reductions in surface and near-surface air temperatures. However, in arid climates, maintaining high vegetation density often requires intensive irrigation, raising concerns regarding water consumption, long-term sustainability, and operational costs. Sparse or strategically distributed vegetation, while more water-efficient, may offer limited thermal relief if deployed without complementary shading or material strategies. As a result, the relationship between vegetation density and cooling effectiveness is nonlinear, and optimal configurations depend on spatial arrangement, canopy structure, and interaction with surrounding infrastructure elements [17]. Evapotranspiration efficiency is a key determinant of landscape cooling performance in hot and dry environments. While evapotranspiration can significantly reduce air temperatures through latent heat flux, its effectiveness is influenced by plant physiology, soil moisture availability, and microclimatic conditions. In arid parks, high solar radiation and low humidity can enhance evapotranspiration rates, but only when adequate moisture is available. Conversely, excessive exposure of vegetated surfaces to direct solar radiation may increase water loss without proportionate cooling benefits, particularly when adjacent pavements remain thermally active. The presence of shaded pavements and built shading structures can improve evapotranspiration efficiency by reducing soil and leaf surface temperatures, thereby moderating moisture loss while sustaining cooling performance [18]. This interdependence highlights the importance of evaluating landscape cooling not as an isolated mechanism, but as part of an integrated thermal system. At the scale of an entire park, landscape cooling manifests as spatially distributed temperature reductions, commonly referred to as park-scale cooling footprints. These footprints extend beyond the immediate vicinity of vegetation, influencing surrounding pedestrian areas and adjacent urban fabric. The magnitude and extent of cooling footprints depend on vegetation coverage, canopy height, spatial continuity of green zones, and interaction with paved and shaded areas [19]. In arid cities, cooling footprints are often fragmented due to discontinuous vegetation patterns and extensive hardscape surfaces, limiting their overall effectiveness. However, when vegetated zones are strategically combined with shaded walkways and thermally optimized pavements, cooling footprints can become more continuous and spatially coherent, enhancing thermal comfort across larger areas. In urban parks such as Zabeel Park, landscape cooling performance is further shaped by the heterogeneity of land cover, including lawns, trees, shrubs, water features, and paved circulation networks. Without coordinated design, high-performing vegetated areas may be thermally undermined by adjacent exposed pavements that act as persistent heat sources. Similarly, irrigation-driven cooling may be offset by increased longwave radiation from surrounding surfaces. These interactions underscore the need for park-scale evaluations that capture both localized cooling effects and their spatial propagation across the park environment [20]. To synthesize existing knowledge and contextualize the approach adopted in this study, Table 3 summarizes key landscape cooling mechanisms, their dominant drivers, and associated limitations in arid park environments.

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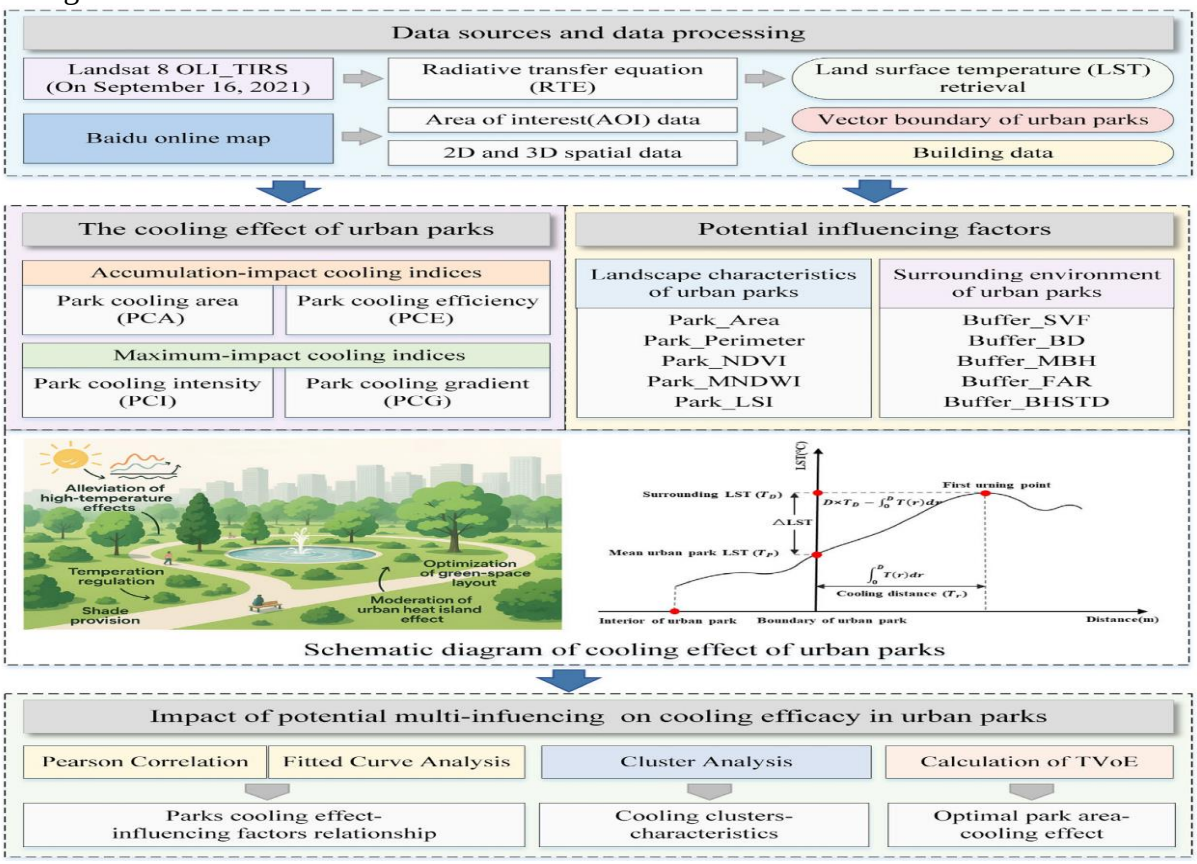
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Table 3: Landscape Cooling Mechanisms and Constraints in Arid Urban Parks

Cooling mechanism	Primary driver	Cooling benefit	Resource constraint	Relevance to this study
Vegetation shading	Canopy density and geometry	Reduction of direct solar radiation	Limited canopy coverage	Evaluated in interaction with shading structures
Evapotranspiration	Soil moisture and plant physiology	Latent heat dissipation	High irrigation demand	Assessed under shaded and unshaded conditions
Park-scale cooling footprint	Spatial continuity of green areas	Area-wide temperature reduction	Fragmentation by hardscape	Integrated with pavement and shading analysis

The spatial manifestation of landscape cooling processes is conceptually illustrated in Figure 2**,** which depicts how vegetation density, evapotranspiration, and shaded hardscape interact to generate park-scale cooling footprints in an arid urban park setting.



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Figure 2: Conceptual representation of landscape cooling dynamics and park-scale cooling footprints in an arid urban park.

The figure illustrates the interaction between vegetated zones, shaded pavements, and exposed hardscape surfaces, highlighting how evapotranspiration and shading contribute to localized and extended cooling effects across pedestrian pathways and open spaces. Overall, landscape cooling in arid parks is governed by complex trade-offs between thermal performance and water efficiency, with vegetation density and evapotranspiration efficiency acting as key mediators [21]. While vegetation alone can provide meaningful cooling benefits, its effectiveness is significantly enhanced when integrated with shading geometry and thermally optimized pavements. At the park scale, the continuity and spatial organization of landscape elements determine the extent of cooling footprints and their contribution to pedestrian thermal comfort. By embedding landscape cooling dynamics within an integrated civil infrastructure framework, this study advances a holistic understanding of how arid urban parks can be designed to deliver maximum thermal relief while minimizing resource demands.

Methodology:

This study adopts an integrated and multiscale methodological approach to comprehensively evaluate urban heat mitigation strategies within arid park environments, acknowledging that thermal performance in outdoor urban spaces does not arise from isolated interventions but from complex interactions across material, human, and spatial scales. Rather than assessing individual mitigation measures independently, the methodology is explicitly designed to establish systematic linkages between pavement thermal behaviour, pedestrian thermal comfort, and park-scale cooling patterns within a unified analytical framework [22]. At the material level, surface thermal responses capture the fundamental heat exchange processes between solar radiation and pavement materials, while at the human scale, these surface conditions are translated into pedestrian-relevant thermal exposure and comfort outcomes. At the broader spatial scale, localized cooling effects are aggregated to evaluate how mitigation strategies influence temperature gradients and cooling footprints across the park environment. By integrating surface-level thermal analysis, pedestrian-oriented thermal assessment, and spatial temperature mapping, the proposed approach captures both the immediate, localized impacts of heat mitigation interventions and their cumulative influence on the surrounding urban microclimate. This multiscale structure allows the evaluation of pavement materials, structural shading geometry, and landscape systems not as discrete or competing elements, but as interdependent components of a coherent civil infrastructure system whose combined performance determines overall thermal resilience [23]. Such an integrated perspective is particularly critical in extreme climatic contexts, where small inefficiencies in material selection, geometric design, or landscape configuration can significantly undermine outdoor thermal comfort. Through this methodology, the study provides a robust and design-relevant framework for understanding and optimizing urban heat mitigation strategies in arid environments.

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Multiscale Evaluation Framework:

The multiscale evaluation framework developed in this study is conceived as a core methodological contribution, responding directly to the complex and scale-dependent nature of thermal processes in arid urban park environments. Urban heat mitigation cannot be adequately understood through single-scale or single-variable analyses, as thermal conditions experienced in outdoor spaces emerge from the cumulative interaction of surface materials, geometric configurations, landscape systems, and human exposure patterns. In arid climates, where solar radiation intensity is extreme and thermal margins are narrow, even localized design decisions can propagate spatially and significantly alter overall microclimatic performance [24]. The proposed framework therefore integrates material-scale, human-scale, and park-scale analyses within a unified methodological structure, ensuring that thermal behaviour is evaluated holistically rather than in isolation. At the foundation of the framework lies the material scale, where pavement surface temperature is treated as the primary indicator of thermal response. Pavement surfaces dominate the energy balance of urban parks in arid cities due to their extensive coverage and high exposure to solar radiation. Surface temperature reflects the combined influence of intrinsic material properties, such as albedo, emissivity, and thermal mass, as well as external modifiers including shading geometry, vegetation proximity, and surrounding land-cover configuration [25]. By focusing on pavement surface temperature under varying exposure conditions, the framework captures the fundamental heat accumulation and dissipation processes that drive near-surface thermal environments. This material-scale assessment establishes a mechanistic baseline from which higher-scale thermal effects emerge. The framework then extends upward to the human scale, recognizing that surface thermal behaviour alone does not fully represent the thermal reality experienced by pedestrians [26]. Outdoor thermal comfort in arid environments is governed by a combination of radiant heat exchange, shading duration, surface temperatures, and localized cooling effects from vegetation. Elevated pavement surface temperatures substantially increase mean radiant temperature, which is a dominant contributor to pedestrian heat stress in hot climates. The human-scale analysis therefore evaluates how material-level thermal responses translate into pedestrian-relevant thermal exposure along walking paths, resting areas, and open spaces within the park. By incorporating shading continuity and landscape interactions, this scale bridges engineering-based surface analysis with human-centred comfort assessment, enabling the evaluation of infrastructure performance in terms of usability and thermal safety rather than purely physical metrics. At the park scale, the framework captures the spatial aggregation of localized thermal processes and their influence on overall park microclimate. Urban parks operate as cooling islands within dense urban fabrics, yet their effectiveness depends strongly on spatial configuration, land-cover heterogeneity, and the integration of pavements, shading structures, and vegetated zones. Park-scale analysis focuses on identifying spatial cooling gradients across the park, including temperature differentials between exposed hardscape, shaded pavements, and vegetated areas, as well as the spatial extent over which cooling effects propagate beyond their immediate sources [27]. These cooling gradients define park-scale cooling footprints, which represent the cumulative thermal influence of integrated mitigation strategies. This scale is essential for evaluating

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whether localized design interventions produce coherent, area-wide cooling benefits or remain thermally fragmented. A defining strength of the multiscale framework lies in its vertical integration of these three analytical levels. Material-scale surface temperatures influence human-scale radiant exposure, which in turn aggregates spatially to shape park-scale cooling patterns. This upward propagation of thermal effects allows the framework to capture nonlinear and synergistic interactions among pavement materials, structural shading geometry, and landscape systems. Rather than evaluating these elements independently, the framework treats them as interdependent components of a single civil infrastructure system whose combined performance determines overall thermal resilience [28]. Such integration is particularly critical in arid environments, where isolated or poorly coordinated interventions may fail to deliver meaningful heat mitigation despite localized improvements. To clarify the scope, variables, and analytical outputs associated with each spatial scale, Table 4 summarizes the structure of the multiscale evaluation framework adopted in this study.

Table 4: Multiscale Evaluation Framework for Urban Heat Mitigation in Arid Parks

Spatial scale	**Primary analytical focus**	**Key thermal indicators**	**Role in integrated assessment**
Material scale	Pavement thermal behaviour	Surface temperature, solar exposure, shading influence	Quantifies heat accumulation and suppression at the surface level
Human scale	Pedestrian thermal environment	Radiant heat exposure, shading duration, near-surface conditions	Translates surface behaviour into human thermal comfort outcomes
Park scale	Spatial cooling performance	Temperature gradients, cooling footprint extent	Evaluates cumulative and area-wide cooling effectiveness

The conceptual linkage among the material, human, and park scales is illustrated in Figure 3, which presents the multiscale evaluation framework developed and applied in this research. The figure visually synthesizes the hierarchical and interactive relationships between pavement-level thermal processes, pedestrian-scale thermal exposure, and park-scale spatial cooling patterns, demonstrating how localized surface responses propagate upward to influence human comfort and area-wide microclimatic performance [29]. By explicitly connecting these scales within a unified schematic, Figure 3 clarifies the causal pathways and feedback mechanisms through which pavement materials, structural shading geometry, and landscape systems jointly determine urban heat mitigation effectiveness in arid park environments.

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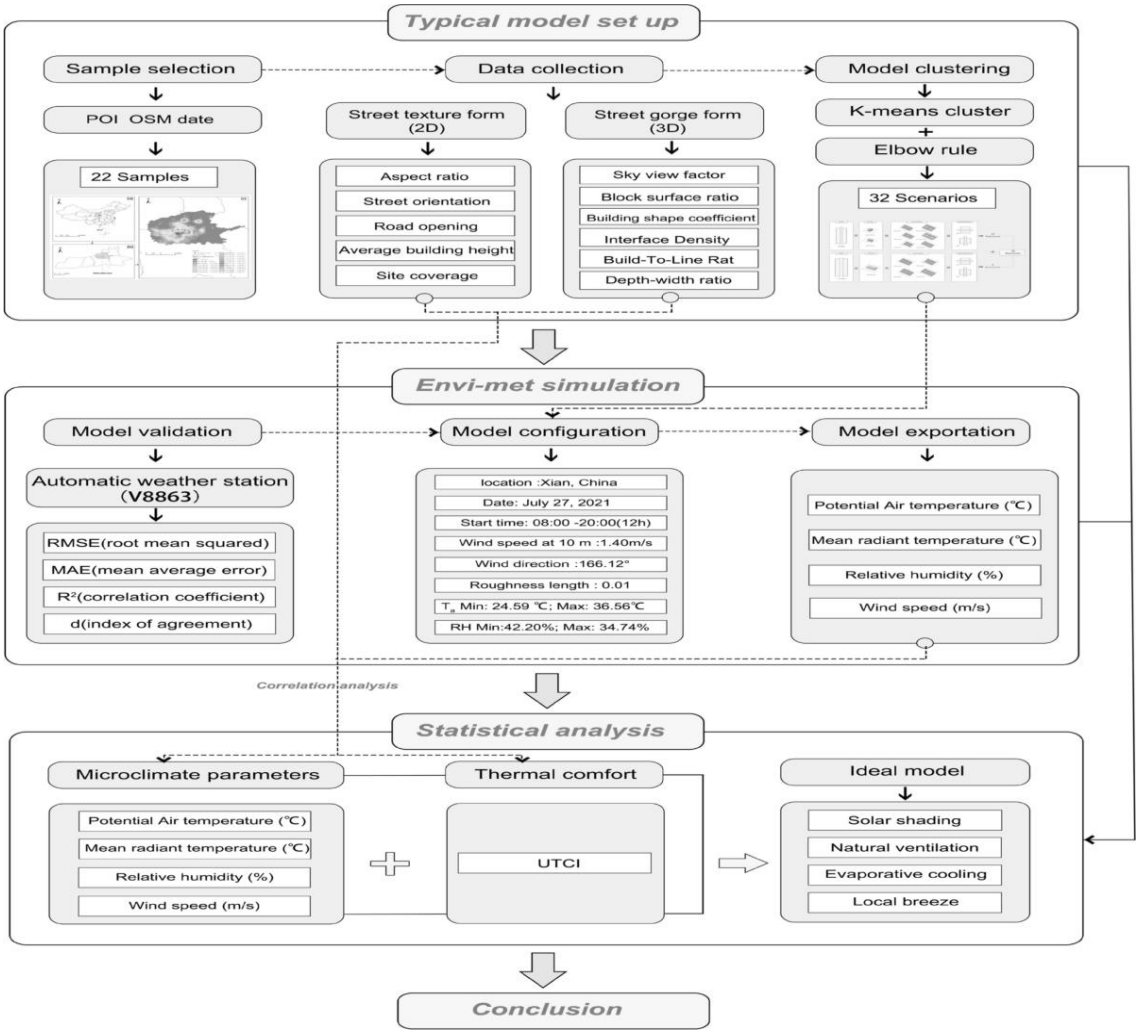


Figure 3: Multiscale evaluation framework integrating pavement surface thermal behaviour, pedestrian thermal comfort, and park-scale spatial cooling gradients.

The figure demonstrates how surface-level heat dynamics influence pedestrian-scale thermal exposure and collectively shape park-scale cooling footprints through the interaction of pavements, shading geometry, and landscape systems. Overall, the multiscale evaluation framework provides a rigorous and design-relevant methodological foundation for this study. By explicitly linking surface thermal behaviour to human comfort and spatial cooling performance, the framework enables a comprehensive assessment of urban heat mitigation strategies that aligns engineering analysis with real-world urban usability [30]. This approach ensures that pavement materials, structural shading geometry, and landscape systems are evaluated not only for their individual thermal performance but also for their combined contribution to thermal resilience in arid urban parks. As such, the framework offers a transferable methodological model for evaluating and optimizing heat mitigation strategies in hot-climate cities facing increasing thermal stress.

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Pavement Thermal Analysis:

Pavement thermal analysis constitutes a central component of the proposed methodology, as pavement surfaces represent the primary interface through which solar energy is absorbed, stored, and re-emitted within arid urban park environments. In cities such as Dubai, extensive hardscape areas are exposed to intense solar radiation for prolonged periods, causing pavements to act as dominant heat reservoirs that elevate near-surface air temperatures and contribute significantly to pedestrian thermal stress. Understanding pavement thermal behaviour is therefore essential for evaluating the effectiveness of urban heat mitigation strategies and for interpreting higher-scale thermal outcomes within the multiscale framework [31]. The analysis focuses on pavement surface temperature as the principal indicator of material-level thermal performance. Surface temperature integrates the effects of intrinsic material properties, including albedo, emissivity, thermal conductivity, and heat capacity, together with external environmental factors such as solar exposure, shading duration, and proximity to vegetated areas. In arid climates, where convective cooling is limited and nocturnal heat release is slow, surface temperature provides a direct and physically meaningful measure of heat accumulation and dissipation at the ground level. Elevated surface temperatures not only increase sensible heat flux to the surrounding air but also intensify longwave radiative exchange with pedestrians, amplifying thermal discomfort [32]. Within this study, pavement thermal behaviour is evaluated under varying exposure conditions to isolate the influence of structural shading geometry and landscape interactions. Pavement segments located under full solar exposure, partial shading, and continuous shading are analysed to capture differences in heat accumulation patterns across typical park circulation zones. This comparative approach allows the identification of how shading continuity and landscape configuration suppress surface heating and reduce peak temperature magnitudes. Particular attention is given to midday and early afternoon periods, during which solar loading and pedestrian thermal stress reach critical levels in arid environments. The temporal dimension of pavement thermal response is also considered, as surface temperatures exhibit strong diurnal variation driven by solar radiation cycles [33]. Rapid heating during morning hours and delayed cooling after sunset are characteristic of pavements with high thermal mass, leading to prolonged thermal discomfort even outside peak solar periods. By examining surface temperature evolution across representative time intervals, the analysis captures both instantaneous thermal conditions and cumulative heat storage effects. This temporal perspective is crucial for understanding how pavement materials interact with shading structures and vegetation to influence short-term comfort and longer-term microclimatic performance. Pavement thermal behaviour is further interpreted in relation to its role within the broader multiscale framework. Material-scale surface temperatures directly influence human-scale thermal exposure by contributing to mean radiant temperature and sensible heat flux in pedestrian zones [34]. At the park scale, spatial patterns of pavement heating and cooling shape temperature gradients and affect the continuity of cooling footprints generated by shading and landscape systems. Consequently, pavement thermal analysis serves as the foundational layer upon which human-scale comfort assessment and park-scale cooling evaluation are built. To clarify the analytical variables and exposure conditions considered in the

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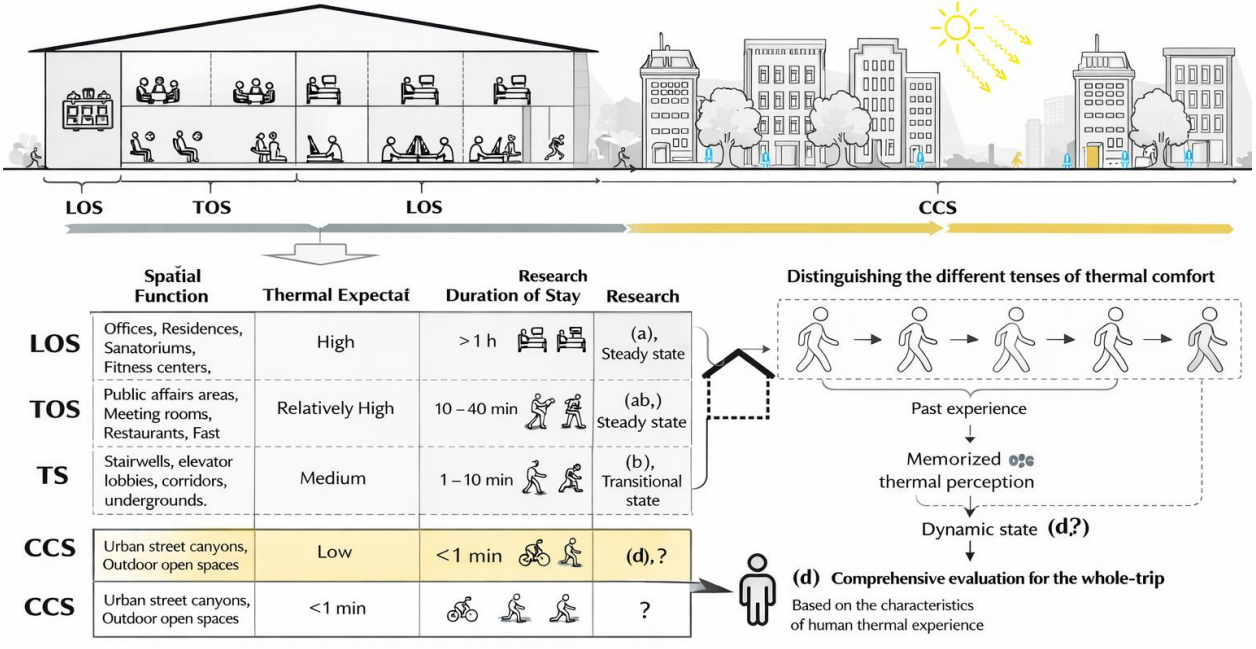
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pavement thermal analysis, Table 5 summarizes the key parameters and their methodological relevance.

Table 5: Key Parameters Considered in Pavement Thermal Analysis

Parameter	Description	Relevance to thermal behaviour
Surface temperature	Pavement skin temperature under varying exposure	Primary indicator of heat accumulation
Solar exposure condition	Full sun, partial shade, continuous shade	Determines shortwave radiation input
Shading duration	Temporal continuity of shadow coverage	Influences peak temperature suppression
Surrounding context	Proximity to vegetation and structures	Modifies convective and radiative exchange

The conceptual relationship between solar exposure, pavement thermal response, and higher-scale thermal impacts is illustrated in Figure 4, which situates pavement thermal analysis within the overall multiscale methodology adopted in this study. The figure demonstrates how variations in solar radiation intensity and shading conditions directly influence pavement surface temperature and heat storage behavior, which in turn shape pedestrian-scale thermal exposure through radiative and sensible heat exchange. These material-level thermal responses further propagate spatially to affect park-scale temperature gradients and cooling footprints, highlighting the role of pavements as a critical intermediary between climatic forcing and human-scale thermal conditions [35]. By embedding pavement thermal analysis within the broader multiscale framework, Figure 4 clarifies the causal pathways through which surface-level heat dynamics contribute to area-wide microclimatic performance in arid urban park environments.



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Figure 4: Pavement thermal behaviour under varying solar exposure

The figure illustrates how surface temperature variations resulting from shading and landscape interactions propagate upward to affect pedestrian thermal exposure and spatial cooling gradients across the park. Overall, the pavement thermal analysis provides critical insight into the material-level mechanisms driving urban heat accumulation in arid parks. By systematically evaluating surface temperature responses under different exposure and shading conditions, this section establishes a robust physical basis for interpreting pedestrian thermal comfort and park-scale cooling performance [36]. The findings from this analysis form a key input to subsequent assessments of shading effectiveness and landscape cooling dynamics, reinforcing the integrated and multiscale nature of the proposed methodology.

Structural Shading Geometry Evaluation:

Structural shading geometry is evaluated in this study as a critical modifier of solar radiation exposure and a key mediator between pavement thermal behaviour and pedestrian-scale thermal comfort. In arid urban parks, where direct solar radiation constitutes the dominant component of the surface energy balance, shading structures play a decisive role in limiting shortwave radiation reaching pavements and pedestrians. The effectiveness of shading, however, is not determined solely by its presence but by its geometric configuration, orientation, height, and temporal alignment with local solar trajectories. Accordingly, this section establishes a systematic methodology for assessing shading performance based on geometric and temporal criteria relevant to extreme desert climates [37]. The evaluation focuses on how different shading geometries influence shadow coverage, shadow duration, and spatial continuity of shaded zones across pedestrian pathways and open areas. Shading structures are assessed in relation to the local solar path, which governs the angle and intensity of incoming radiation throughout the day. In low-latitude cities such as Dubai, high solar altitudes during summer months result in short but intense midday shadows and elongated shadows during morning and late afternoon periods. Shading geometries that are not explicitly aligned with these solar characteristics may offer limited thermal protection during peak heat hours, despite appearing adequate from a static or aesthetic perspective. The methodology therefore emphasizes time-dependent shading performance rather than instantaneous or static shadow presence. Shadow duration is treated as a key performance indicator, as continuous shading is essential for suppressing pavement heat accumulation and reducing longwave radiative exchange with pedestrians [38]. Intermittent shading allows pavements to reheat rapidly, undermining the cumulative cooling effect and increasing radiant heat loads at the human scale. The evaluation accounts for both the duration and continuity of shading along pedestrian routes, recognizing that fragmented shadow patterns may provide limited comfort benefits even when overall shaded area appears substantial. This approach ensures that shading performance is assessed in a manner directly relevant to pedestrian experience and thermal safety. The interaction between structural shading and pavement thermal behaviour is explicitly incorporated into the evaluation. Shading geometries are analysed in terms of their ability to reduce pavement surface temperatures, delay peak heating, and suppress thermal re-radiation [39]. These effects are particularly important in arid environments, where pavements

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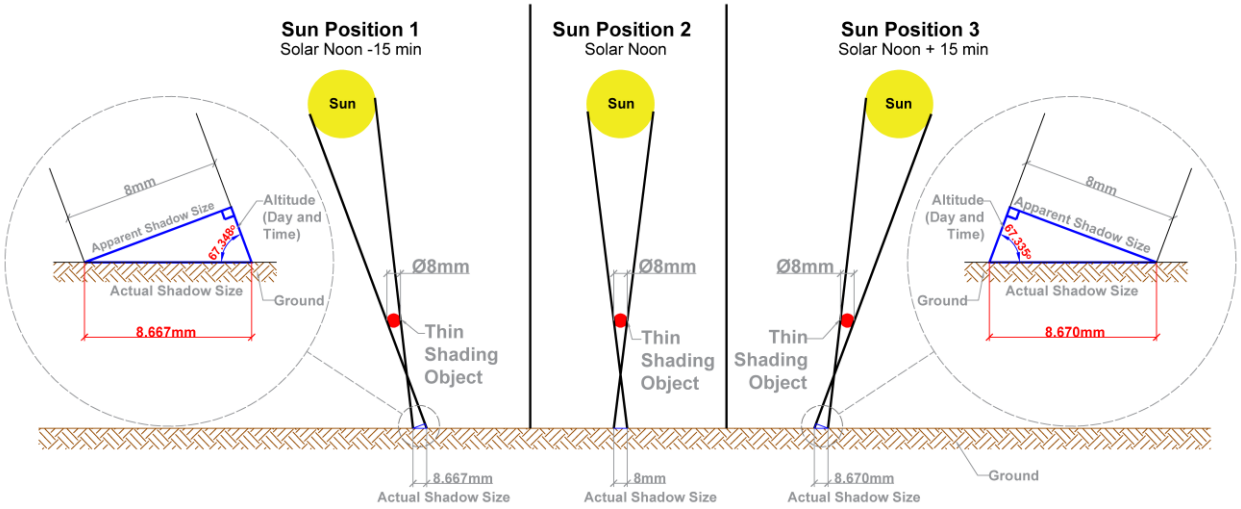
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with high thermal mass can remain hot long after solar exposure decreases. By linking shading geometry to material-scale thermal responses, the methodology ensures that shading effectiveness is evaluated not only in terms of geometric shadow metrics but also in terms of tangible thermal outcomes. Structural shading is also evaluated in its interaction with landscape elements. In urban parks, built shading structures often coexist with tree canopies and landscaped zones, creating overlapping or competing shadow patterns [40]. Without coordinated design, such interactions may lead to redundant shading in some areas and insufficient coverage in others. The methodology therefore considers the spatial integration of built and vegetative shading, assessing how combined shading systems influence shadow continuity, pavement cooling, and pedestrian comfort. This integrated perspective addresses a common limitation in existing studies, which frequently evaluate built and natural shading independently. To clarify the geometric and temporal parameters considered in the structural shading evaluation, Table 6 summarizes the key variables and their methodological significance.

Table 6: Parameters Used for Structural Shading Geometry Evaluation

Parameter	Description	Thermal relevance
Shading geometry	Shape, height, and orientation of shading structures	Determines shadow length and coverage
Solar path alignment	Relationship between shading geometry and solar altitude/azimuth	Governs temporal effectiveness of shading
Shadow duration	Continuity of shading over time	Influences cumulative pavement cooling
Shadow continuity	Spatial coherence of shaded zones	Affects pedestrian thermal comfort

The methodological integration of shading geometry with solar path and thermal effects is illustrated in Figure 5, which conceptually situates shading evaluation within the multiscale framework.



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Figure 5: Shading geometry evaluation based on solar path alignment and its influence on pavement thermal behaviour and pedestrian thermal exposure.

The figure shows how different shading geometries produce varying shadow lengths and durations across the day, influencing pavement surface temperatures and pedestrian comfort within an arid urban park. The structural shading geometry evaluation provides a critical link between material-scale pavement thermal analysis and human-scale thermal comfort assessment. By explicitly incorporating solar path dynamics, shadow duration, and spatial continuity, the methodology captures the temporal and geometric dimensions of shading performance that are often overlooked in conventional design evaluations. This approach ensures that shading structures are assessed not merely as architectural features, but as functional components of heat-resilient civil infrastructure. The findings from this section inform subsequent landscape cooling analysis and contribute directly to the integrated assessment of park-scale thermal performance under extreme climatic conditions.

Landscape Cooling Assessment:

Landscape cooling assessment forms the third analytical pillar of the proposed methodology and focuses on quantifying the cooling contribution of vegetation and landscaped surfaces within an arid urban park environment. In desert cities, landscape systems represent one of the few mechanisms capable of actively reducing ambient and near-surface air temperatures through biophysical processes, particularly evapotranspiration and shading. However, unlike built shading or pavement-based strategies, landscape cooling is strongly constrained by water availability, plant physiology, and spatial configuration. The methodology therefore evaluates landscape cooling not as an isolated ecological process, but as an integrated component of the broader civil infrastructure system that interacts dynamically with pavements and structural shading. The assessment emphasizes the role of vegetation in modifying the surface energy balance by reducing sensible heat flux and promoting latent heat exchange. Vegetated surfaces dissipate absorbed solar energy through evapotranspiration, thereby lowering surface and surrounding air temperatures. In arid environments, this cooling potential is highly sensitive to vegetation density, canopy structure, and irrigation regimes [41]. Excessively dense vegetation may provide strong localized cooling but at the cost of high water demand, while sparse vegetation may be water-efficient yet thermally ineffective if deployed without complementary shading or material strategies. The methodology therefore considers vegetation performance in relation to both thermal benefit and resource efficiency, recognizing that sustainable heat mitigation in arid parks requires balancing these competing objectives. Evapotranspiration efficiency is treated as a central performance indicator in the landscape cooling assessment. Rather than focusing solely on absolute evapotranspiration rates, the methodology examines how effectively available moisture is converted into thermal cooling under varying exposure conditions. In highly exposed environments, vegetation may experience elevated water loss without proportional cooling benefits, particularly when adjacent pavements remain hot and radiatively active. The presence of shaded pavements and built shading structures can enhance evapotranspiration efficiency by lowering leaf and soil surface temperatures, reducing moisture stress, and sustaining cooling over longer periods. The

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methodology therefore evaluates landscape cooling in conjunction with shading geometry and pavement thermal behaviour, capturing synergistic interactions that amplify overall thermal performance. At the spatial level, the assessment extends to park-scale cooling effects, which are expressed through spatial cooling gradients and cooling footprints [42]. Cooling footprints represent the spatial extent over which vegetated and shaded areas measurably influence thermal conditions beyond their immediate boundaries. In arid urban parks, these footprints are often fragmented due to discontinuous vegetation patterns and extensive hardscape areas. The methodology evaluates how the spatial distribution of vegetation, in combination with shaded pavements, influences the continuity and reach of cooling effects across the park. This approach enables the identification of zones where landscape interventions generate coherent, area-wide cooling benefits and areas where cooling effects are suppressed or localized due to surrounding thermal loads. The landscape cooling assessment is fully embedded within the multiscale framework established in Section 4.1. At the material scale, vegetation influences pavement surface temperatures by providing shade and moderating radiative exchange. At the human scale, evaporative cooling and shaded microclimates reduce pedestrian thermal exposure and enhance outdoor comfort. At the park scale, the aggregation of these localized effects determines the magnitude and spatial coherence of cooling gradients across the entire park environment. By explicitly linking these scales, the methodology ensures that landscape performance is evaluated in terms of both localized cooling mechanisms and their cumulative spatial impact. To clarify the key variables and analytical focus of the landscape cooling assessment, Table 7 summarizes the primary parameters considered and their relevance to thermal performance in arid parks.

Table 7: Parameters Considered in Landscape Cooling Assessment

Parameter	**Description**	**Thermal relevance**
Vegetation density	Spatial coverage and canopy distribution	Determines shading and cooling potential
Evapotranspiration efficiency	Cooling per unit of available moisture	Indicates thermal effectiveness under water constraints
Shading interaction	Overlap with built shading and pavements	Enhances cooling efficiency and duration
Cooling footprint	Spatial extent of thermal influence	Reflects park-scale cooling performance

The conceptual relationship between vegetation, evapotranspiration, and spatial cooling effects is illustrated in Figure 6, which situates landscape cooling within the integrated multiscale methodology.

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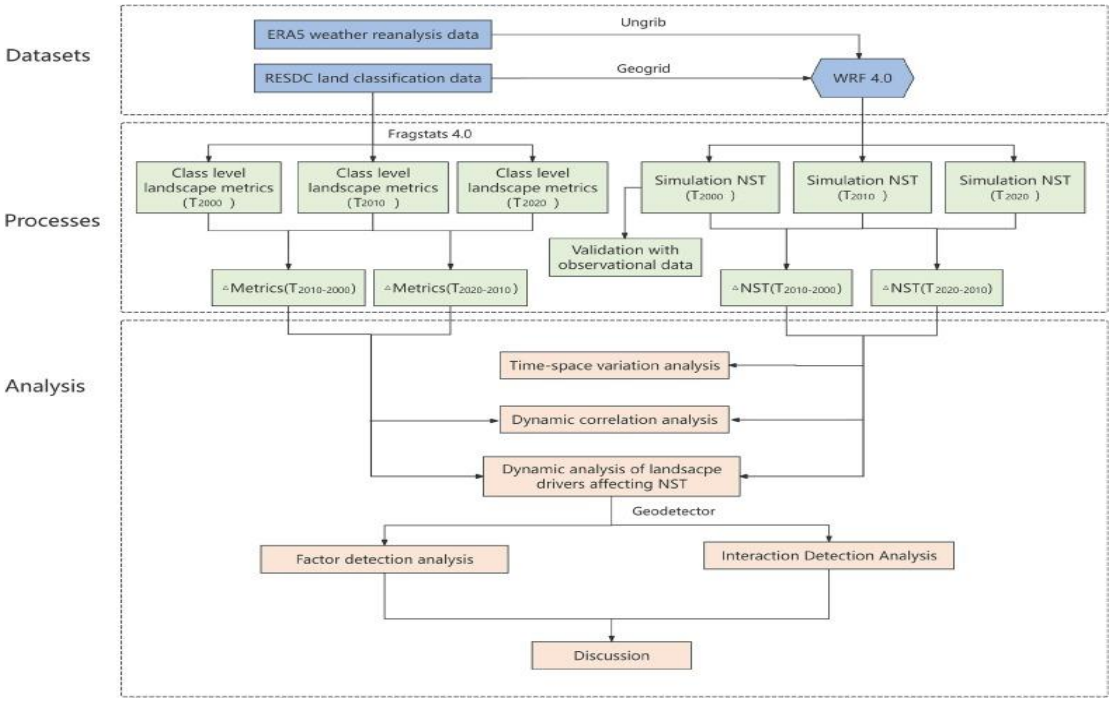


Figure 6: Landscape cooling assessment.

The figure illustrates how localized cooling generated by vegetation propagates spatially across the park, moderated by pavement thermal behaviour and structural shading geometry. Overall, the landscape cooling assessment provides a critical ecological and spatial dimension to the proposed methodology. By evaluating vegetation performance in terms of evapotranspiration efficiency, interaction with shading and pavements, and park-scale cooling footprints, the methodology captures the full contribution of landscape systems to urban heat mitigation in arid environments. This integrated assessment ensures that landscape interventions are evaluated not only for their localized cooling effects but also for their role in enhancing pedestrian comfort and strengthening park-scale thermal resilience under extreme climatic conditions.

Results and Discussion:

The results of this study provide clear evidence that urban heat mitigation performance in arid park environments is governed by strong interactions between pavement thermal behaviour, structural shading geometry, and landscape cooling processes across multiple spatial scales. The findings confirm that these strategies do not operate independently; rather, their combined effects produce nonlinear and scale-dependent thermal responses that significantly influence pedestrian comfort and park-scale microclimatic performance. This section discusses the results sequentially across material, human, and park scales, while emphasizing their interconnections and implications for civil infrastructure design in extreme climatic conditions. At the material scale, pavement surface temperature analysis reveals substantial thermal contrasts between exposed, partially shaded, and continuously shaded pavements. Exposed pavements consistently exhibit the highest surface temperatures throughout

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the diurnal cycle, confirming their role as dominant heat reservoirs in arid urban environments. Shaded pavements demonstrate marked reductions in peak surface temperature, with the magnitude of reduction strongly correlated with shading duration and continuity. Pavements located adjacent to vegetated zones further exhibit moderated thermal behaviour, indicating that landscape proximity enhances surface cooling by reducing radiative exchange and promoting localized convective and evaporative processes. These results reinforce the importance of integrating shading and landscape elements with pavement design rather than relying solely on material properties. Temporal analysis of pavement surface temperatures highlights that shading influences not only peak temperatures but also the rate of heat accumulation and release. Shaded pavements show slower morning heating and reduced late-afternoon thermal persistence compared to fully exposed surfaces. This delayed heat buildup and accelerated cooling are particularly important in arid climates, where stored heat often prolongs thermal discomfort well beyond peak solar hours. The findings demonstrate that effective pavement heat mitigation requires interrupting cumulative heat storage, rather than merely reducing instantaneous solar exposure. To summarize key material-scale findings, Table 8 presents a comparative overview of pavement thermal responses under different exposure conditions.

Table 8: Pavement Surface Temperature Response under Different Exposure Conditions

Exposure condition	**Peak surface temperature trend**	**Diurnal heating behaviour**	**Thermal implication**
Fully exposed pavement	Highest peak temperatures	Rapid heating and slow cooling	Strong heat storage and re-radiation
Partially shaded pavement	Moderately reduced peaks	Interrupted heating pattern	Limited thermal relief
Continuously shaded pavement	Lowest peak temperatures	Delayed heating and faster cooling	Effective heat suppression
Shaded + vegetated pavement	Lowest and most stable temperatures	Moderated diurnal variation	Enhanced cooling synergy

At the human scale, the translation of material-level thermal behaviour into pedestrian thermal conditions reveals pronounced differences in perceived thermal stress across park pathways. Pedestrian zones characterized by exposed pavements and fragmented shading exhibit elevated radiant heat loads, resulting in thermally hostile conditions during peak daytime hours. In contrast, pathways combining continuous shading with nearby vegetation consistently demonstrate reduced thermal exposure and improved comfort conditions. These findings confirm that pavement surface temperature is a major contributor to pedestrian mean radiant temperature, particularly in environments where direct solar radiation dominates the thermal balance. The continuity of shading emerges as a decisive factor in human-scale thermal comfort. While isolated or intermittent shadows reduce direct solar exposure momentarily, they

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fail to provide sustained relief due to rapid pavement reheating and longwave radiation emission. Continuous shading, especially when aligned with pedestrian movement corridors, produces more stable and comfortable thermal environments [43]. The results also show that the overlap between built shading structures and vegetated zones produces compounded cooling benefits by simultaneously reducing radiant heat flux and enhancing evaporative cooling. These outcomes highlight a critical limitation in many existing park designs, where shading structures and landscape elements are implemented independently. The present findings demonstrate that pedestrian comfort benefits are maximized only when shading geometry, pavement materials, and vegetation are spatially coordinated. This reinforces the need for integrated design approaches that prioritize human-scale thermal experience rather than isolated performance metrics. At the park scale, spatial temperature mapping reveals distinct cooling gradients and cooling footprints generated by landscape and shading interventions. Vegetated areas function as localized cooling nodes through evapotranspiration, but their influence is often spatially constrained when surrounded by extensive exposed hardscape. In such cases, cooling effects dissipate rapidly, limiting the park's ability to function as an effective thermal refuge. However, when vegetated zones are connected through shaded pavements and continuous pedestrian corridors, cooling effects propagate more effectively across the park, resulting in broader and more coherent cooling footprints. Spatial analysis further indicates that fragmented park designs produce uneven thermal environments with sharp temperature gradients between shaded and exposed areas [44]. These gradients can undermine pedestrian comfort by forcing users to traverse thermally hostile zones between isolated cool pockets. Conversely, integrated designs characterized by coordinated shading, vegetation, and thermally moderated pavements produce smoother spatial gradients and expanded cooling footprints, enhancing both comfort and usability at the park scale. The park-scale cooling performance observed in this study is summarized in Table 9**,** which links spatial configuration to cooling effectiveness.

Table 9: Park-Scale Cooling Performance under Different Spatial Configurations

Spatial configuration	**Cooling footprint extent**	**Thermal uniformity**	**Park-scale effectiveness**
Isolated vegetation pockets	Limited	Highly uneven	Low
Vegetation without shaded pavements	Moderate	Fragmented	Moderate
Shaded pavements without vegetation	Moderate	Localized	Moderate
Integrated shading–pavement–landscape	Extensive	Smooth gradients	High

From a resource-efficiency perspective, the results demonstrate that landscape cooling effectiveness in arid parks is strongly influenced by evapotranspiration efficiency

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rather than vegetation density alone. Vegetation exposed to full solar radiation exhibits high water demand without proportional cooling benefits, whereas vegetation integrated with shading and cooler pavements sustains effective cooling with moderated moisture loss. This finding has important implications for water-sensitive urban design, suggesting that integrated infrastructure strategies can simultaneously enhance thermal performance and reduce irrigation requirements. The integrated nature of the results is conceptually illustrated in Figure 7**,** which synthesizes the multiscale interactions observed across the study.

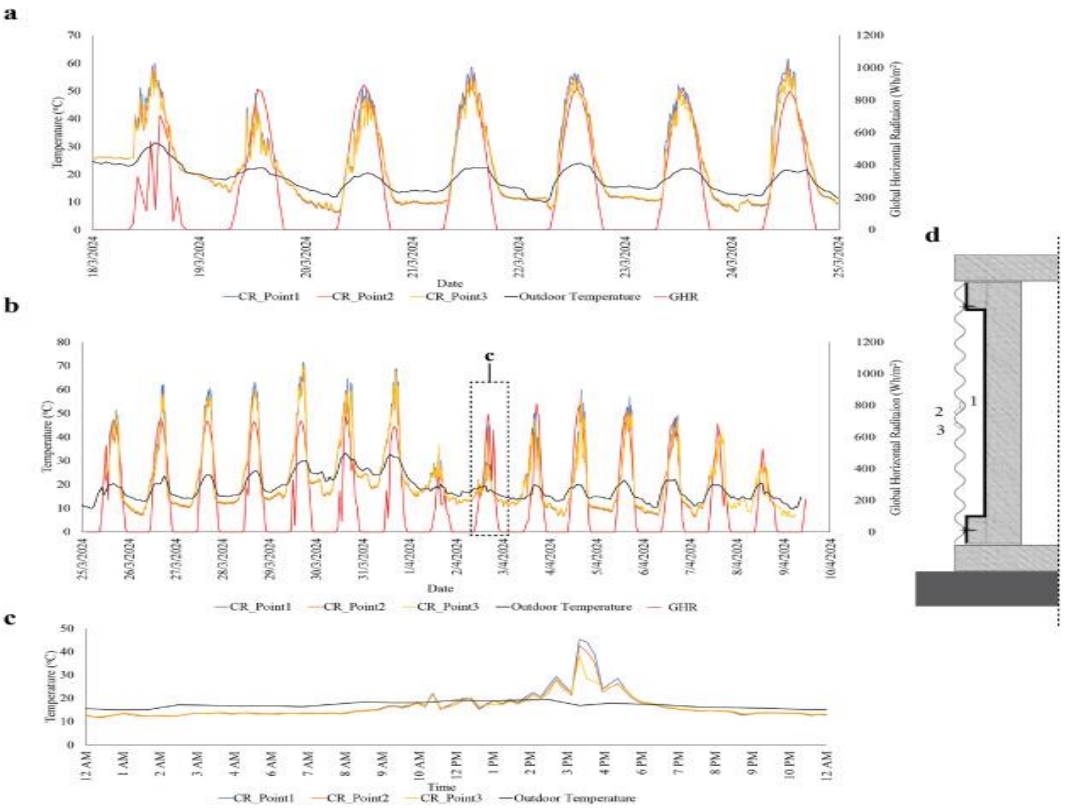


Figure 7: Integrated results illustrating the interaction between pavement thermal behaviour, structural shading geometry, and landscape cooling across material, human, and park scales.

The figure shows how surface-level thermal suppression translates into pedestrian comfort improvements and expands park-scale cooling footprints when mitigation strategies are spatially and temporally coordinated. In comparison with existing literature, the findings extend current understanding by demonstrating that the combined performance of pavement, shading, and landscape strategies exceeds the sum of their individual effects when evaluated within an integrated multiscale framework. While prior studies have reported localized benefits of individual interventions, this study empirically demonstrates their synergistic and nonlinear interactions in a real arid park context. The results therefore address a critical research gap and provide evidence-based guidance for designing heat-resilient public spaces in desert cities. Overall, the results confirm that effective urban heat mitigation in arid

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parks requires a paradigm shift from isolated interventions toward integrated civil infrastructure strategies. By aligning pavement materials, structural shading geometry, and landscape systems across material, human, and park scales, urban parks such as Zabeel Park can deliver sustained thermal relief, improved pedestrian comfort, and enhanced microclimatic resilience under extreme climatic conditions.

Future Work:

While this study provides an integrated and multiscale evaluation of urban heat mitigation strategies in an arid park environment, several avenues remain open for further investigation to extend and deepen the findings. Future research should focus on advancing both the methodological sophistication and the practical applicability of integrated heat mitigation frameworks for extreme climatic contexts [45]. One important direction for future work is the incorporation of long-term temporal analysis to capture seasonal and interannual variability in thermal performance. The present study primarily examines representative thermal conditions under extreme heat scenarios; however, extending the analysis across different seasons would enable a more comprehensive understanding of how pavement materials, shading geometry, and landscape systems perform under varying solar angles, wind regimes, and humidity levels. Such longitudinal assessments would also allow evaluation of thermal lag effects, nighttime cooling behaviour, and seasonal shifts in pedestrian usage patterns, which are critical for year-round park usability [46]. Future studies could also integrate advanced microclimate simulation and digital twin technologies to enhance predictive capability and design optimization. Coupling high-resolution computational models with real-time or long-term monitoring data would enable dynamic assessment of thermal performance under alternative design scenarios, including changes in shading geometry, vegetation density, or pavement materials. The use of digital twins could further support scenario-based planning, allowing designers and policymakers to evaluate trade-offs between thermal comfort, water consumption, and construction costs before implementation. Another promising research direction involves the explicit integration of artificial intelligence and optimization techniques into urban heat mitigation design. Machine learning models and multi-objective optimization algorithms could be employed to identify optimal combinations of pavement properties, shading configurations, and landscape layouts that maximize thermal comfort while minimizing resource use, particularly water demand in arid regions [47]. Such approaches would build upon the multiscale framework developed in this study by automating design exploration and revealing non-intuitive synergies among mitigation strategies. From a human-centred perspective, future work should incorporate behavioural and perceptual dimensions of thermal comfort. While this study evaluates pedestrian thermal exposure based on physical and microclimatic indicators, integrating user perception surveys, behavioural observations, or adaptive comfort models would provide deeper insight into how different populations experience and respond to thermal environments. This would be especially valuable in culturally and demographically diverse cities such as Dubai, where thermal tolerance and usage patterns vary widely. Further research is also needed to investigate the long-term durability and maintenance implications of integrated heat mitigation strategies. Pavement ageing, vegetation growth cycles,

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irrigation system performance, and shading structure maintenance can all influence thermal effectiveness over time. Evaluating how these factors evolve and interact would support more resilient and cost-effective infrastructure planning, ensuring that thermal benefits are sustained throughout the lifecycle of urban parks. Finally, future studies should explore the transferability and scalability of the proposed framework to other arid and semi-arid urban contexts. Applying the methodology to different park typologies, street canyons, transit-oriented developments, and mixed-use districts would test its robustness and adaptability. Comparative studies across cities in the Gulf region and other desert climates would further strengthen the generalizability of the findings and contribute to the development of regionally informed guidelines for heat-resilient urban design. Overall, future research building on this work has the potential to transform integrated urban heat mitigation from a largely descriptive practice into a predictive, optimized, and human-centred discipline, supporting the development of sustainable and thermally resilient civil infrastructure in the face of escalating climatic stress.

Conclusion:

This study proposed an integrated civil infrastructure approach to urban heat mitigation in arid park environments through a multiscale evaluation of pavement thermal behaviour, structural shading geometry, and landscape cooling dynamics, with Zabeel Park in Dubai serving as a representative case study. By linking material-scale surface processes, human-scale thermal exposure, and park-scale spatial cooling patterns, the research addresses a key limitation in existing studies that have largely examined heat mitigation strategies in isolation. The results demonstrate that pavements act as major contributors to heat accumulation in arid cities, while appropriately designed shading geometries play a crucial role in suppressing surface temperatures and limiting radiant heat transfer. Landscape systems further enhance cooling performance through evapotranspiration and shading, particularly when spatially coordinated with pavements and structural shading. Importantly, the findings reveal that integrated strategies generate synergistic cooling effects that exceed the performance of individual interventions. At the pedestrian scale, the combined use of shaded pavements and vegetation significantly improves outdoor thermal comfort, emphasizing the importance of human-centred design in heat-resilient public spaces. At the park scale, coordinated integration of materials, shading, and landscape elements produces more continuous cooling footprints and smoother thermal gradients, enabling urban parks to function more effectively as thermal refuges within dense urban environments. Overall, this study contributes a transferable, multiscale evaluation framework that supports evidence-based design and planning of heat-resilient urban parks in arid climates. By demonstrating the effectiveness of integrated civil infrastructure strategies, the research provides practical insights for enhancing thermal comfort, sustainability, and microclimatic resilience in cities facing increasing heat stress.

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