

Article

Overheating Resilience of Shading Systems Across Climates: A Systematic Evidence Synthesis Using a Multiscale KPI Framework

Francesco Sommese ^{1,*}  and Shady Attia ² ¹ Department of Civil, Building and Environmental Engineering (DICEA), University of Naples Federico II, 80125 Naples, Italy² Sustainable Building Design Laboratory, Department of Urban and Environmental Engineering (UEE), Faculty of Applied Sciences, Université de Liège, 4000 Liège, Belgium; shady.attia@uliege.be

* Correspondence: francesco.sommese@unina.it

Abstract

Climate change is intensifying overheating risks in cities, where the Urban Heat Island effect and increasingly severe recent heatwaves are driving up thermal stress, cooling demand, and outdoor discomfort. Shading is among the most effective passive strategies for reducing solar-radiative exposure, yet research on shading systems remains fragmented across building and urban scales, climatic contexts, and performance indicators, limiting comparability across studies. This paper develops a multiscale, cross-climate KPI framework for assessing shading systems for overheating resilience. Based on a PRISMA-based review of 90 publications, the framework draws on the IPCC climate-risk and vulnerability literature and develops an operationalisation of exposure, sensitivity, and adaptive capacity tailored to shading-related overheating resilience. It proposes a multidimensional classification of shading systems by application scale, physical mechanism, and temporal behaviour, and a harmonised KPI set that distinguishes climate-invariant definitions from climate-sensitive assessments requiring local calibration. The framework is then applied to a structured database of 46 case studies, showing that most indicators are stable in formal definition but not in interpretation—several units required climate-dependent calibration. Recurring associations emerge between physical mechanism, application scale, and climatic context, while tropical and continental climates and morphological self-shading remain markedly under-represented in the current evidence base. The framework does not rank shading solutions or validate performance outcomes; rather, it offers a structured methodological basis for selecting, interpreting, and calibrating KPIs in future empirical and simulation-based research on climate-resilient shading.



Academic Editor: Giridharan Renganathan

Received: 3 September 2026

Revised: 3 October 2026

Accepted: 5 October 2026

Published: 8 October 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: urban heat island; heatwave resilience; overheating risk; climate-adaptive shading; passive cooling strategies; cross-climate KPI framework; built environment vulnerability; multiscale resilience assessment; solar-radiative exposure; climate-sensitive

1. Introduction

Climate change is increasing overheating risks in buildings and urban spaces, driven by rising air and surface temperatures, more frequent and severe heatwaves, and the amplification of thermal stress by the Urban Heat Island (UHI) effect [1–6]. These conditions affect indoor and outdoor thermal comfort, cooling demand, peak electricity loads, and the resilience of the built environment under heat stress [5,7–11]. Overheating should

therefore be considered not only a building-performance issue, but also a multiscale urban challenge involving solar exposure, thermal response, energy demand, and outdoor environmental conditions.

Solar exposure is a key driver of overheating in both buildings and urban spaces. Shading can reduce incident solar radiation before it is converted into sensible heat, thereby limiting solar gains, surface heating, mean radiant temperature, and thermal discomfort. Its effectiveness, however, depends on application scale, physical mechanism, temporal behaviour, climatic context, and the performance indicator used to assess it. Building-scale shading primarily affects envelope solar gains and indoor thermal conditions, whereas urban shading also modifies pedestrian exposure, surface temperatures, and outdoor thermal comfort. Recent heatwaves have also highlighted the limitations of approaches that address overheating mainly through building-level regulations or technological systems. A growing body of research supports a more systemic approach in which urban-scale adaptation measures complement, and in some cases precede, building-level mitigation. The “*Cooling Ladder 2.0*” [12], for example, emphasises a hierarchy in which urban measures such as vegetation, shading, reflective materials, and ventilation corridors contribute to reducing ambient heat before progressively moving toward building-level passive measures, efficient systems, and active cooling. However, the evidence remains fragmented across building and urban scales, shading typologies, climatic contexts, and performance indicators. This fragmentation makes it difficult to determine which Key Performance Indicators (KPIs) can be compared across contexts, which require climate-specific calibration, and how different shading mechanisms relate to exposure reduction, thermal sensitivity, and adaptive capacity.

Within this context, climate resilience has become an important concept in built-environment research. Climate resilience refers to the ability of buildings and urban systems to absorb, adapt to, and respond to climatic stresses while maintaining acceptable performance under extreme and variable conditions [13,14]. Here, however, resilience is considered in a bounded sense, referring specifically to the contribution of shading solutions to overheating-risk reduction rather than to the full spectrum of climate hazards. This perspective requires approaches that move beyond average climatic conditions and consider robustness and adaptive capacity under progressive warming and extreme heat events.

Shading systems are a key component of this approach because they modulate solar exposure, reduce unwanted heat gains, and can improve indoor and outdoor thermal comfort while contributing to lower cooling demand. Their effects extend across spatial scales. At the building scale, shading primarily influences envelope heat gains, indoor thermal conditions, daylight availability, and cooling demand, whereas at the urban scale it affects pedestrian solar exposure, mean radiant temperature, surface overheating, outdoor thermal comfort, and local microclimatic conditions. These scales should therefore be considered complementary, as overheating emerges from interactions among urban form, outdoor microclimate, building envelopes, and human exposure.

The effectiveness of shading, however, is highly dependent on climatic context and latitude, which influence solar geometry, seasonal radiative inputs, and the balance between cooling requirements and solar access. The same shading solution may therefore perform differently in hot-arid, hot-humid, Mediterranean, or temperate conditions. Shading systems should consequently be selected and evaluated according to climatic conditions, latitude, application scale, and temporal behaviour rather than treated as universally transferable solutions.

Despite the extensive literature on shading systems, existing evidence remains fragmented across spatial scales, climatic contexts, and evaluation criteria. Building-scale studies generally focus on indoor comfort and energy-performance indicators, whereas urban-scale studies tend to prioritise microclimatic parameters and outdoor comfort. Per-

formance indicators are also defined and applied heterogeneously, often according to the requirements of individual case studies, with limited attention to their comparability across climates, latitudes, and scales. As a result, it remains unclear which shading-performance indicators can be directly compared across contexts and which require local calibration before interpretation.

A systematic assessment of shading as an overheating-resilience strategy therefore requires a framework capable of integrating shading classification, performance indicators, spatial scale, and climatic context within a common structure. Such a framework should also clarify how different indicators relate to the mechanisms through which shading contributes to overheating-risk reduction, including exposure reduction through solar-radiation control, sensitivity mitigation through reduced thermal response and cooling demand, and adaptive capacity through dynamic, seasonal, or responsive behaviour.

1.1. Novelty

Existing approaches provide valuable foundations for understanding shading performance, including OSAM [15], classification-oriented façade studies [16], and multi-scale urban-canyon simulations [17]. These studies demonstrate that shading performance is influenced by climate, morphology, and application context, but they do not provide an operational criterion for determining which KPIs can be directly compared across climatic contexts and which require local calibration before interpretation.

This study addresses this gap by using the IPCC climate-risk and vulnerability literature as a conceptual reference and developing an operational KPI interpretation tailored to shading-related overheating resilience. The proposed framework distinguishes between KPIs that are climate-invariant in definition and those that are climate-sensitive in interpretation. Climate-invariant does not imply climate-independent: it indicates that the metric definition remains stable across climatic contexts, while its target values, thresholds, and design relevance may vary with climate, latitude, season, and use patterns. Climate-sensitive indicators, in contrast, require explicit consideration of local reference conditions or thresholds before cross-context interpretation.

The novelty therefore lies not simply in proposing another classification of shading systems, but in translating these dimensions into a multiscale KPI framework that explicitly retains climatic specificity while supporting structured comparison. The framework is subsequently examined against a systematically assembled body of empirical evidence spanning different climates, spatial scales, shading mechanisms, and KPI families.

1.2. Objective and Research Questions

Against this background, the present study has four main objectives. First, it develops a multiscale KPI-based framework for assessing shading systems by integrating building- and urban-scale applications within a unified overheating-resilience structure. Second, it classifies performance indicators according to their resilience contribution—exposure reduction, sensitivity mitigation, or adaptive capacity—and their degree of climate transferability. Third, it applies the framework to a structured database of 46 published case studies extracted and coded according to a transparent protocol. Fourth, it examines the distribution of shading typologies, physical mechanisms, temporal behaviours, climatic contexts, spatial scales, and KPI families within the assembled evidence base, identifying recurring associations and assessing the consistency of the proposed framework across heterogeneous studies.

In line with these objectives, the work focuses on four principal research questions:

- What are the main concepts and analytical dimensions associated with overheating-resilient shading solutions?

- How can shading systems be classified and their performance indicators harmonised across different scales, climate zones, and latitudes?
- How can classification and key performance indicators be integrated into a coherent framework for comparing shading strategies across building and urban scales?
- How is the existing empirical evidence on shading-system performance distributed across scales, climates, typologies, and KPI families, and to what extent does the proposed framework support its structured interpretation?

The scope of the study is limited to shading systems as strategies for overheating resilience and climate adaptation, with particular attention to their contribution to reducing solar exposure, thermal discomfort, and cooling demand under current and future climatic conditions. Both building-scale and urban-scale applications are considered, recognising that shading effectiveness depends on spatial scale, climatic context, solar geometry, and temporal behaviour. The study does not address climate resilience in its full multi-hazard meaning; rather, it focuses specifically on the contribution of shading to overheating resilience in the built environment.

This study is conceived as an evidence-based synthesis combining systematic evidence mapping, framework development, and structured analysis of published case studies. Its purpose is not to establish universal performance rankings or experimentally validate the framework, but to determine whether heterogeneous evidence on shading systems can be organised and interpreted consistently across spatial scales, climatic contexts, shading mechanisms, and KPI families.

2. Methodology

This study adopts an evidence-based synthesis approach in which published literature is used as structured evidence to develop and apply a multiscale KPI framework for overheating-resilient shading. The methodology (Figure 1) combines systematic literature review, evidence mapping, conceptual classification, KPI harmonisation, structured case-study extraction, and descriptive quantitative and narrative synthesis.

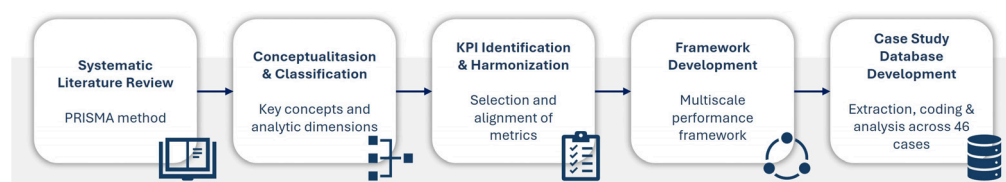


Figure 1. Methodological steps for developing the performance framework for climate-resilient shading solutions.

The study does not include original empirical monitoring or a dedicated simulation campaign; all quantitative evidence derives from previously published field measurements, simulations, and combined studies, extracted and coded according to the protocol described in Section 2.4. The framework was applied to 46 published case studies to assess its ability to organise and interpret the available evidence. This application should not be understood as experimental validation, since no original monitoring or simulation campaign was conducted.

2.1. Literature Review

The methodological process began with a systematic literature review conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol aimed at mapping evidence on shading systems, passive cooling approaches, and performance indicators relevant to overheating resilience in the built environment. The

review covered studies operating at both building and urban scales, with particular attention to evaluation methods, KPI selection, climatic dependencies, and assessment practices across different climate zones and latitudinal contexts. The review was not intended to produce a meta-analysis of numerical performance outcomes, but to identify recurring shading typologies, performance domains, indicators, and interpretation criteria relevant to the construction of the proposed multiscale KPI framework.

Review Protocol

The literature search was conducted in March 2026 using Scopus as the sole bibliographic database. Scopus was selected because it provides broad multidisciplinary coverage of research concerning building performance, urban microclimate, passive cooling, shading systems, and thermal comfort. Web of Science was not included because institutional access was not available during the review period. Accordingly, the review should be understood as a Scopus-based systematic evidence synthesis rather than an exhaustive search across multiple bibliographic databases.

The search was limited to publications in English published from 2000 to March 2026. Peer-reviewed journal articles, conference proceedings, and review papers were considered. Selected reports and technical documents issued by recognised international institutions were additionally consulted to support the conceptual framing of the study, but they were not treated as part of the primary bibliographic search corpus unless retrieved through the defined selection procedure.

The Scopus search was applied to titles, abstracts, and keywords using the following Boolean query:

("shading system*" OR "solar shading" OR "shading device*" OR "dynamic shading" OR "static shading" OR "adaptive shading" OR "green shading" OR "vegetation shading" OR "tree canopy" OR "urban shading" OR "self-shading" OR "solar control") AND ("overheating" OR "heat stress" OR "thermal stress" OR "thermal resilien*" OR "urban heat island" OR "climate resilien*" OR "passive cooling") AND ("built environment" OR "building*" OR "urban microclimate" OR "outdoor comfort" OR "thermal comfort").

The screening, eligibility assessment, and data extraction were conducted by the two authors. The identified publications were divided between them, and each author applied the same predefined inclusion and exclusion criteria and structured extraction scheme to publications assigned to them. The review protocol was not preregistered. The review was conducted following the PRISMA reporting framework (Figure 2) and predefined inclusion and exclusion criteria.

The search process initially identified 354 records. After removing duplicates ($n = 12$), 342 records were screened. Titles and abstracts were reviewed to exclude contributions not directly related to shading systems, solar control strategies, or heat-related performance aspects, resulting in 78 records excluded and 264 records selected for full-text assessment.

Full-text articles were assessed against predefined inclusion and exclusion criteria, leading to the exclusion of 174 records and a final selection of 90 publications.

Studies were included if they:

- addressed shading or solar control strategies applied to building-scale, urban-scale, or multiscale built-environment context;
- provided a quantitative or structured qualitative discussion of performance aspects related to solar radiation, overheating, thermal comfort, cooling demand, urban microclimate, or heat stress;
- reported, proposed, or discussed performance indicators, evaluation metrics, or assessment criteria applicable to shading systems;

- demonstrated relevance to overheating mitigation, heat-related climate adaptation, or thermal resilience.

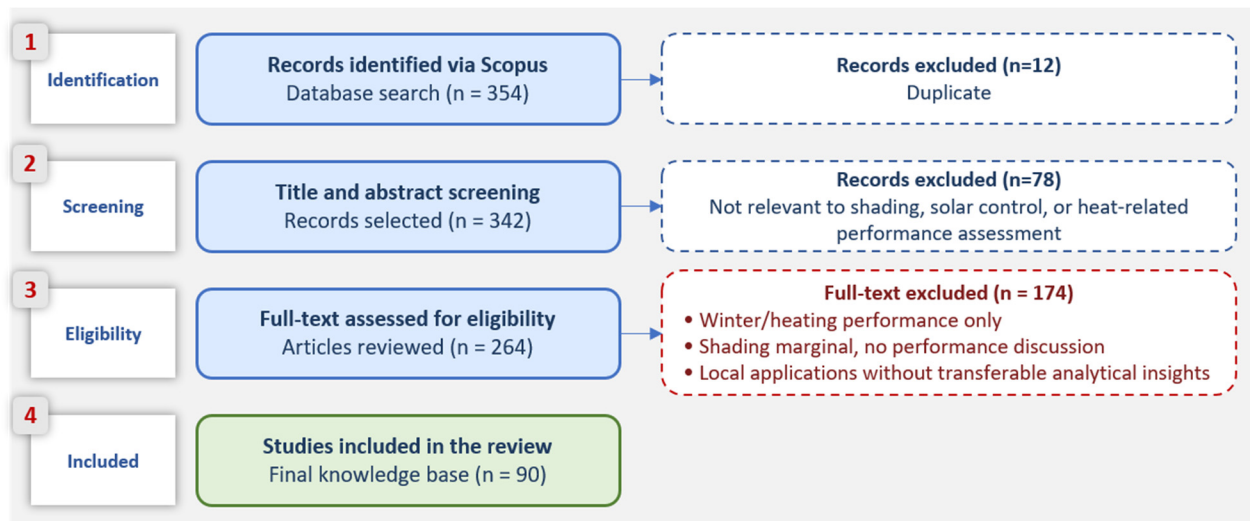


Figure 2. PRISMA flow diagram.

Studies were excluded if they:

- focused exclusively on winter performance or solar gains for heating purposes;
- considered shading only as a secondary or marginal design aspect without performance-related discussion;
- addressed climatic hazards unrelated to overheating without a clear connection to solar control, heat exposure, or thermal comfort;
- were limited to local applications whose findings could not be linked to transferable indicators, assessment procedures, climatic variables, or shading typologies.

Location-specific case studies were not excluded per se. They were excluded only when the reported results did not provide transferable methodological or analytical insights relevant to the framework.

The 90 included publications were analysed through a structured extraction process. For each contribution, information was extracted on: (i) the shading system or solar-control strategy considered; (ii) the application scale; (iii) the physical shading mechanism and temporal behaviour; (iv) the performance indicators adopted; (v) the performance domain addressed; (vi) the climatic variables, latitudinal context, and boundary conditions influencing interpretation; and (vii) the assessment method, including simulation, monitoring, experimental analysis, review, or mixed approaches.

The extracted information was subsequently used in two ways: first, to support the classification of shading systems according to application scale, physical mechanism, and temporal behaviour; and second, to organise KPIs according to their relationship with exposure reduction, sensitivity mitigation, adaptive capacity enhancement, and climate dependency. This targeted evidence synthesis provides the methodological basis for the proposed multi-scale cross-climate KPI framework.

2.2. Conceptualisation and Definition of Overheating-Resilience Shading

Based on the previous stage, the study identifies the key analytical dimensions needed to conceptualise shading systems as strategies for overheating resilience in the built environment. In line with the revised scope of the paper, resilience is not addressed as a general multi-hazard concept but is operationalised in relation to heat-related risk, solar-radiative exposure, indoor and outdoor thermal comfort, and cooling demand.

The conceptualisation is structured through an author-defined operationalization of exposure, sensitivity, and adaptive capacity, informed by IPCC climate-risk and vulnerability literature [18,19]. In this context, exposure refers to the solar-radiative input reaching buildings, urban surfaces, and pedestrians before thermal effects occur; sensitivity refers to the resulting thermal response, including indoor overheating, surface temperature increase, outdoor thermal discomfort, and cooling demand; and adaptive capacity refers to the ability of shading systems to modulate their performance over time in response to diurnal variability, seasonal solar geometry, heatwaves, and long-term warming.

The main analytic dimensions adopted in the framework are:

- application scale, distinguishing building-scale, urban-scale, and multiscale/interface systems;
- physical shading mechanism, distinguishing artificial/technological, nature-based/vegetative, morphological self-shading, and hybrid systems;
- temporal behaviour, distinguishing static/fixed, dynamic/operable, seasonal/ecological, and adaptive/responsive systems;
- performance domain, including solar-radiative control, thermal-response mitigation, cooling-demand reduction, and temporal modulation of shading performance;
- climatic and latitudinal context, which conditions solar geometry, overheating risk, seasonal performance, and the interpretation of climate-sensitive indicators.

Within this framework, shading systems are not assessed in terms of absolute performance values at this stage. Rather, they are conceptualised as passive and adaptive strategies whose relevance depends on their interaction with climate-dependent variables such as solar geometry, local microclimate, latitude, urban morphology, and temporal variability. This conceptualization provides the methodological basis for the subsequent classification of shading systems and harmonisation of KPIs across building and urban scales.

2.3. KPI Identification and Harmonisation

This step integrates the identification and harmonisation of KPIs into a coherent framework for overheating-resilient shading solutions. The aim is to organise performance indicators according to the analytical dimensions defined above, enabling structured comparison across spatial scales, climatic contexts, and latitudinal conditions.

KPI selection followed a three-tier approach: (i) indicators defined by international standards; (ii) indicators used in peer-reviewed studies on shading systems, building thermal performance, urban microclimate, and outdoor thermal comfort; and (iii) indicators derived from established physical principles governing solar radiation, heat transfer, and thermal response, when supported by scientific literature.

The selected KPIs were organised according to the three resilience dimensions adopted in the study. Indicators related to solar-radiative control were associated with exposure reduction; indicators describing indoor or outdoor thermal response, comfort, surface temperature, or cooling demand were associated with sensitivity mitigation; and indicators capturing dynamic, seasonal, operable, or responsive behaviour were associated with adaptive capacity enhancement.

The harmonisation process does not involve the calculation, normalisation, or ranking of KPI values. Rather, it establishes a structured interpretative framework that clarifies KPI definitions, performance domains, applicable shading typologies, baseline conditions, and calibration requirements for future empirical or simulation-based applications.

Distinguishing Climate-Invariant and Climate-Sensitive

A specific distinction is introduced between climate-invariant definitions and climate-sensitive assessments (Figure 3). In this study, climate-invariant does not mean climate-

independent. It indicates that the operational definition, unit of measurement, and calculation procedure of a KPI remain stable across climatic contexts, even though target values, thresholds, design relevance, and interpretation may vary with climate, latitude, season, urban morphology, and use conditions.

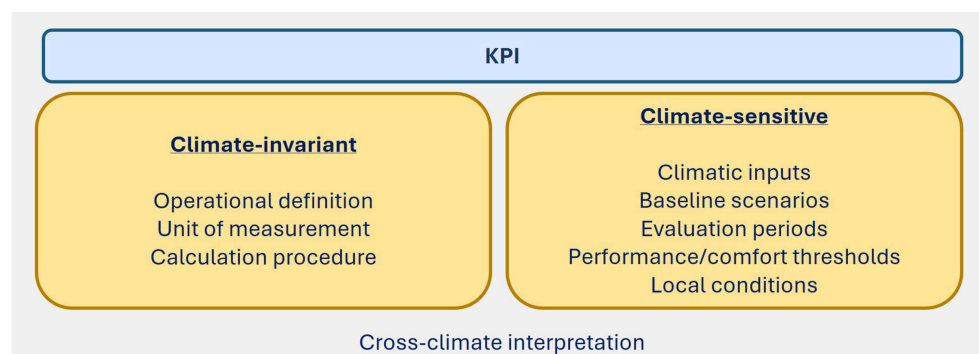


Figure 3. Conceptual distinction between climate-invariant KPI definitions and climate-sensitive assessments.

Climate-sensitive assessments, by contrast, require explicit calibration of climatic inputs, baseline scenarios, evaluation periods, and comfort or performance thresholds before cross-climate comparison. The distinction therefore concerns the level at which climate dependency enters the assessment: for climate-invariant KPIs, climate mainly affects interpretation; for climate-sensitive KPIs, climate affects the assessment conditions themselves.

2.4. Case Study Database Development and Framework Application

To move beyond a purely conceptual assessment framework and evaluate its applicability against real-world evidence, the framework was subsequently applied to a database of published case studies extracted from the 90 publications identified through the systematic literature review (Figure 4). While the broader review supported the construction of the conceptual multiscale KPI framework, this second stage was designed to populate the framework with empirical evidence, allowing the analytical dimensions to be applied against reported case-study data rather than discussed only at a conceptual level.

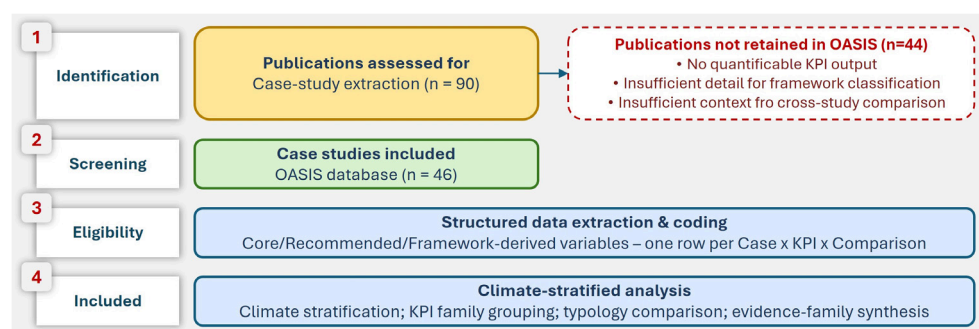


Figure 4. Flow diagram of identification, extraction, coding, and analysis of 46 case studies.

For the purposes of this database, a case study is defined as one publication (one DOI) reporting at least one quantifiable shading-related outcome. Where a single publication reports multiple KPIs, comparison conditions, building types, or monitoring sites, these are captured as separate rows within the same case rather than as separate cases.

Of the 90 publications included in the systematic review, a total of 46 case studies met the additional OASIS (*Overheating and Shading Indicators Dataset for Built Environment*

Resilience) database inclusion criteria and were selected for detailed analysis. The 44 publications that did not meet the additional OASIS inclusion requirements were retained in the broader systematic-review evidence base but were not entered into the case-level database. Exclusion decisions were based on the additional criteria described above and were made before framework-derived coding. The selected cases:

- reported at least one quantifiable baseline-to-post-intervention comparison, or an equivalent directional outcome, for a shading-related KPI;
- specified the application scale, physical shading mechanism, and temporal behaviour of the intervention with sufficient detail to be classified according to the framework presented in Section 2.2;
- provided enough contextual information—location, climate classification, and methodological approach—to support cross-study comparison.

The 46 case studies were first selected based on the availability and adequacy of the reported evidence; only subsequently were the retained cases coded according to the analytical framework. The remaining publications were retained in the broader evidence base but were not included in the case-level database because they did not provide sufficient quantitative or contextual information for the structured analysis. The selected cases covered a wide range of climatic contexts, geographical locations, building and urban typologies, shading mechanisms, and methodological approaches, including field measurements, simulation-based studies, experimental investigations, and combined methodologies.

The resulting structured database OASIS is openly available via Harvard Dataverse [20].

Data Extraction and Coding Scheme

To ensure the systematic and consistent collection of evidence across heterogeneous studies, a structured data extraction and coding scheme was developed and applied to all selected case studies in the OASIS database. The scheme was designed to capture both information directly reported in the original publications and framework-derived variables required for the subsequent resilience-oriented analysis.

The coding scheme comprised three main categories of variables, reflecting differences in reporting consistency across the literature and in the epistemic status of the information recorded:

- Core extracted variables, directly reported in the original studies and treated as mandatory for a case to be included in the database: bibliographic information, DOI, climatic and geographical descriptors, shading-system characteristics (typology and physical mechanism), methodological approach, KPI definitions, measurement units, and reported performance outcomes, including baseline and post-intervention values or, where a single comparable numerical pair was not reported, a directional quantitative outcome.
- Recommended contextual variables, extracted whenever reported but not treated as grounds for excluding a case when absent: latitude, intervention dimensions, temporal resolution and evaluation period, absolute and percentage change (calculated directly from baseline and post-intervention values where both were reported as single, comparable figures), uncertainty indicators and model validation metrics—recorded as distinct fields to separate measurement or reporting precision from model fidelity—and study limitations. No formal methodological quality or risk-of-bias assessment was performed. The recorded information on uncertainty, model validation, and study limitations was instead used as contextual information during evidence interpretation.
- Framework-derived variables, generated during the coding process to support application of the proposed assessment framework rather than extracted directly from the literature, and visually and structurally separated from the extracted data to preserve

the distinction between primary evidence and interpretation. These included the resilience dimension associated with each KPI (Exposure, Sensitivity, or Adaptive Capacity), the classification of KPI transferability, the need for local calibration, and the identification of primary and secondary resilience contributions.

To facilitate comparison across studies, each row of the database was structured according to a Case $\times$ KPI $\times$ Comparison logic: each row represents a single case $\times$ KPI $\times$ comparison entry, and where a study reported multiple KPIs, each combination was recorded as a separate row. Case-level descriptors such as location, climate, shading typology, and methodological characteristics were repeated identically for every KPI entry associated with a given case study. This approach enhanced database consistency and improved subsequent filtering, statistical analysis, and evidence synthesis procedures, without requiring reconstruction of case-level context for each KPI.

In addition, each indicator was assigned to a broader KPI Family to account for the diversity of performance domains addressed in the literature. Three primary families were considered:

- Thermal and Overheating Performance;
- Visual and Daylighting Performance;
- Energy Performance.

This classification was introduced after preliminary extraction indicated that several shading interventions (particularly kinetic and biomimetic façade systems) were evaluated in the source literature through daylighting or glare indicators alongside, or instead of, thermal metrics. Rather than restricting the database to overheating-specific indicators, the KPI Family classification was adopted to preserve this evidence and to enable analysis of how different performance domains are represented across shading typologies and climatic contexts, consistent with the framework's premise that the transferability of a KPI depends on the properties of the indicator itself, not solely on climatic context.

Particular attention was devoted to the assessment of KPI transferability across climates. Following the conceptual framework proposed in this study, two distinct coding questions were applied to each indicator:

1. Is the KPI definition physically or mathematically invariant across climatic contexts?
2. Is the interpretation, threshold, or performance target of the KPI climate-dependent?

This distinction was adopted because a single invariant/sensitive label conflated two analytically distinct questions, which do not necessarily covary: a KPI may have a stable definition while still requiring locally calibrated thresholds for meaningful interpretation. It allowed indicators to be evaluated beyond a simple binary climate-invariant/climate-sensitive classification and provided a more robust basis for assessing cross-climate comparability and calibration requirements.

The resulting database constituted the empirical foundation for the subsequent synthesis and comparative analysis, enabling the investigation of relationships between climatic conditions, shading typologies, resilience dimensions, and performance outcomes across the 46 collected case studies.

2.5. Comparability and Synthesis Strategies

Before synthesis, candidate Case $\times$ KPI $\times$ Comparison rows were screened for comparability according to three criteria: the physical nature and location of the measured quantity, the temporal basis of the reported value, and the type of baseline comparison. Indicators sharing a nominal KPI label were not pooled when they referred to physically different quantities, such as indoor air temperature, outdoor pedestrian-level air temperature, or façade-gap microclimate conditions. Similarly, instantaneous peaks, diurnal means,

and aggregated ranges were treated separately where their direct combination would have obscured the meaning of the reported effect.

Reported uncertainty and model-validation metrics were recorded where available and considered when interpreting individual outcomes. They were not used as formal exclusion criteria, because reporting was inconsistent across the reviewed studies; however, values approaching the reported level of measurement or model uncertainty were identified in the synthesis.

Evidence families represented by at least ten cases, spanning more than one climate group and satisfying the above comparability criteria, were synthesised using descriptive quantitative summaries. Case-level mean and maximum reductions were summarised descriptively by climate group. These summaries were intended to describe the distribution of reported case-level outcomes within each climate group rather than to estimate a pooled intervention effect or a climate-specific effect. The case remained the primary unit of evidence, and no weighting by sample size, measurement precision, or study design was applied. This procedure does not constitute a formal meta-analysis, since it does not use variance-weighted pooled effect sizes, confidence intervals, or heterogeneity statistics. Where sufficient observations were available, the dispersion of case-level outcomes was retained through case-level ranges and individual values reported in the corresponding tables. For each case and KPI, one case-level mean and one case-level maximum were derived from the corresponding OASIS rows: the mean is the reported average, or the arithmetic mean of the reported scenario, point, or site values (the midpoint when only a range is given), and the maximum is the largest reduction reported for that case. In the tables, reductions carry their sign (negative = cooling, positive = warming) and are averaged with their sign, so that null or adverse outcomes are retained; in the text, reductions are expressed as positive magnitudes. Means and maxima are averaged separately, each over the cases reporting that statistic (NR = not reported), and the denominators are stated separately for means and maxima; a case reporting only one of the two statistics contributes only to that summary. Cases whose reference condition differs from the shaded-versus-unshaded (or vegetated-versus-bare) comparison, such as a façade-gap measurement or a comparison against an existing shade sail, were not pooled.

Evidence families that did not meet these conditions because of limited sample size, single-climate representation, heterogeneous units, or incompatible comparison structures were retained for structured narrative synthesis and evidence mapping. This two-tier strategy enabled descriptive quantitative comparison where the published evidence was sufficiently comparable while preserving evidence that could not be meaningfully pooled.

3. Conceptualizing Overheating-Resilience for Shading Systems

Resilience is commonly understood as the capacity of socio-technical and urban systems to withstand disturbances, adjust to changing conditions, and reorganise when existing configurations become inadequate [13,21–28].

In the built environment, this concept is often operationalised through three complementary capacities: absorptive capacity, adaptive capacity, and transformative capacity [29]. Absorptive capacity refers to the ability to withstand and cope with disturbances; adaptive capacity refers to incremental adjustments that allow systems to maintain function under changing conditions; and transformative capacity refers to structural changes enabled by learning, innovation, and reorganisation. In the context of building cooling, previous research has likewise proposed domain-specific operationalisations of resilience, including absorptive capacity, adaptive capacity, restorative capacity, and recovery speed, highlighting the need to translate broader resilience concepts into assessment criteria suited to thermal performance and cooling systems [30].

In this study, resilience is not addressed as a general multi-hazard property of the built environment. Rather, it is deliberately narrowed to overheating resilience, understood as the capacity of building and urban systems to reduce heat exposure, limit indoor and outdoor thermal discomfort, reduce cooling demand, and maintain acceptable performance under heatwaves, seasonal extremes, and long-term warming trends. This focus reflects the central hazard addressed in the paper: overheating driven by solar radiation exposure, elevated air and surface temperatures, and the degradation of thermal comfort in buildings and open spaces.

Urban resilience provides the broader conceptual background for this interpretation, since cities must respond to multiple shocks and stresses, including environmental, social, infrastructural, and climatic disruptions [31–33].

However, the present study does not aim to develop a general theory of urban resilience. Instead, it adopts a climate-risk-oriented perspective in which overheating is treated as a specific and increasingly critical stressor for the built environment. From this perspective, the most relevant resilience properties are robustness and flexibility [22]: robustness refers to the capacity of urban and building configurations to maintain acceptable thermal performance during heat stress, while flexibility refers to the ability of systems to adjust their performance across diurnal, seasonal, and long-term climatic variability. The transition from urban resilience to climate resilience is therefore interpreted here in a bounded sense. Climate resilience is considered only in relation to heat-related risks, rather than to the full spectrum of climatic hazards. Although hydro-geological risks, stormwater management, and ecosystem services are relevant dimensions of urban climate adaptation [34–36], they do not constitute the main assessment domain of this framework. They may be considered co-benefits when associated with hybrid or nature-based shading solutions, but the primary focus remains thermal: overheating risk, solar radiation exposure, cooling demand, and indoor and outdoor thermal comfort.

To make this resilience lens operational, the study draws on the IPCC climate-risk and vulnerability framework [18] and on related exposure-sensitivity-adaptive capacity vulnerability studies [19] as a conceptual reference, but does not assume a one-to-one correspondence between the IPCC terminology and the performance characteristics of shading systems. In particular, the present study develops an author-defined operationalisation of selected vulnerability dimensions for the specific problem of overheating-resilient shading.

The relationship between the climate-risk and vulnerability concepts discussed above and shading-specific performance is operationalised in this study through three analytical dimensions: radiative exposure, thermal sensitivity, and shading-system adaptive capacity (Figure 5).

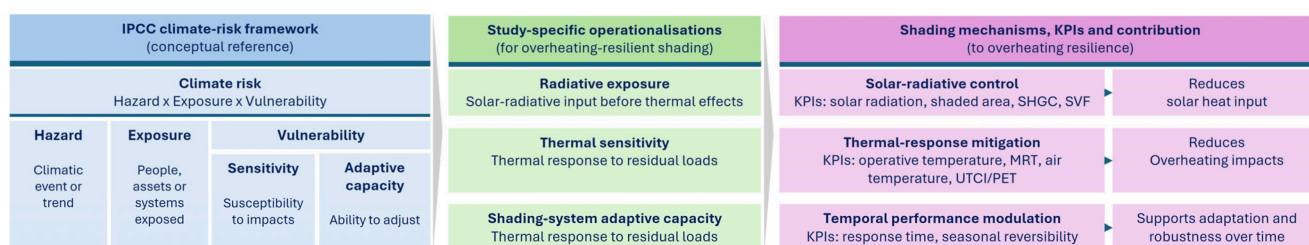


Figure 5. Author-developed operationalisation of climate-risk and vulnerability concepts for shading-related overheating resilience.

Radiative exposure refers to the solar-radiative input reaching buildings, urban surfaces, or pedestrians before thermal effects occur. Thermal sensitivity refers to the thermal response of indoor and outdoor environments to residual radiative and climatic loads.

Shading-system adaptive capacity refers to the ability of a shading system to modulate or maintain its performance over time under varying climatic, seasonal, or operational conditions.

In this study, adaptive capacity is deliberately operationalised as a property of the shading system. It therefore refers to the technical, biological, configurational, or operational capacity of the shading solution to adjust or maintain its performance across changing conditions. It does not represent the broader adaptive capacity of the exposed population, institution, community, or urban system, which may include social, economic, governance, behavioural, and infrastructural dimensions. This narrower operationalisation is adopted because the objective of the framework is to assess shading systems as physical and environmental adaptation mechanisms rather than to provide a comprehensive assessment of societal vulnerability.

These three dimensions provide the analytical structure for the KPI framework developed in the following sections. Exposure-related KPIs describe radiative control before thermal effects occur; sensitivity-related KPIs describe the resulting thermal and comfort response; and adaptive-capacity KPIs describe temporal modulation, reversibility, or persistence of shading performance.

On this basis, overheating-resilient shading solutions are defined as building and urban shading elements, systems, or configurations designed to reduce solar-radiative exposure, mitigate indoor and outdoor thermal stress, and support temporal adaptation to heatwaves, seasonal variability, and long-term warming through static, dynamic, nature-based, morphological, or hybrid mechanisms.

4. Classification of Shading Systems

This section develops a conceptual and descriptive classification of shading systems based on application scale, physical shading mechanism, temporal behaviour, and functional contribution to overheating resilience. The proposed classification has a structural and methodological purpose: it does not aim to evaluate or compare the performance of different solutions, but to organise shading typologies according to the mechanisms through which they reduce solar-radiative exposure, mitigate thermal sensitivity, and support adaptive capacity.

A key limitation of conventional classifications is that categories such as static, dynamic, adaptive, artificial, and nature-based are often treated as mutually exclusive, although they describe different properties of a shading system. A nature-based solution may be static, seasonal, or adaptive; an artificial device may be fixed, operable, or responsive; and a morphological configuration may produce shading without being a discrete add-on device. For this reason, the present study adopts a multidimensional classification based on four complementary dimensions: application scale, physical shading mechanism, temporal behaviour, and primary contribution to overheating resilience.

The application scale distinguishes between building-scale, urban-scale, and multiscale or interface systems. The physical shading mechanism identifies how shading is produced, distinguishing artificial or technological systems, nature-based or vegetative systems, morphological self-shading, and hybrid systems. The temporal behaviour describes whether the system remains fixed, can be operated, changes seasonally, or responds adaptively to climatic or user-related conditions. Finally, the resilience contribution links each solution to the analytical dimensions of exposure reduction, sensitivity mitigation, and adaptive capacity enhancement.

4.1. Scale of Application: Building, Urban, and Multiscale Interface Systems

The building and urban scales are not interpreted as opposing domains, but as complementary levels of overheating mitigation. At the building scale, shading primarily regulates

solar gains through the envelope, influencing indoor operative temperature, daylight availability, glare risk, and cooling demand. At the urban scale, shading modifies pedestrian solar exposure, surface heating, mean radiant temperature, outdoor thermal comfort, and local microclimatic conditions. Some systems operate at the interface between these scales, simultaneously affecting façade exposure and outdoor environmental conditions. Examples include green façades, vegetated pergolas, porticoes, arcades, courtyards, and street trees adjacent to building envelopes.

This scale-based distinction is therefore analytical rather than oppositional. Building-scale shading addresses the thermal response of indoor environments to solar gains, while urban-scale shading reduces the ambient and radiative conditions that contribute to overheating before they affect buildings and pedestrians. This multiscale interpretation is consistent with the overheating-resilience focus of the framework, in which shading is understood as a distributed passive infrastructure acting across both envelope and urban microclimate.

4.2. Physical Shading Mechanisms

4.2.1. Artificial and Technological Shading Systems

Artificial and technological shading systems include man-made elements specifically designed to control solar radiation through geometry, material properties, optical modulation, or mechanical movement. At the building scale, this category includes horizontal overhangs, vertical fins, brise-soleil, light shelves, mashrabiya and jaali screens, venetian blinds, sliding panels, movable louvers, chromogenic glazing systems, and adaptive façade components [37–44].

The underlying principle of these systems is the interception, filtering, reflection, or modulation of incident solar radiation before it produces thermal effects on building envelopes, urban surfaces, or pedestrians. Fixed artificial devices rely mainly on geometric obstruction and are strongly influenced by orientation, latitude, and solar altitude. Operable or adaptive systems add a temporal dimension by allowing the degree of solar control to vary according to climatic conditions, user needs, or control strategies. In resilience terms, artificial and technological systems primarily contribute to exposure reduction and, when dynamic or responsive, to adaptive capacity enhancement. At the building scale, the technological evolution of the envelope has progressively transformed the façade from a static barrier into a dynamic and complex interface capable of regulating energy flows between indoor and outdoor environments [37,38]. Adaptive façades are defined as envelope components capable of reversibly responding to short-term climatic fluctuations or changing occupant requirements [37,42,43]. These systems include movable mechanical devices, chromogenic technologies, active solar façades, and ventilated façade systems that combine solar control with convective regulation [42,44]. Mechanical adaptive systems may rely on rotation, translation, folding, bending, stretching, or twisting mechanisms [38,40,45], while control strategies can be extrinsic, based on sensors and actuators, or intrinsic, where responsiveness is embedded in material properties [46,47].

Advanced adaptive systems also include biomimetic components, smart materials, Shape Memory Alloys, Shape Memory Polymers, thermal bimetals, and hygroscopic wood, which enable passive or active responsiveness to environmental stimuli [37,45–50].

4.2.2. Nature-Based and Vegetative Shading Systems

Nature-based and vegetative shading systems employ vegetation as a source of solar-radiative control and microclimatic regulation. At the building scale, they include green façades, living walls, climbing plants, vegetated screens, and vegetated systems either integrated into or detached from the building envelope [51–53]. At the urban scale, they

include street trees, urban forests, parks, vegetated pergolas, hedges, vegetative barriers, and other green infrastructure elements whose canopy or foliage contributes directly to shading [54–59].

For the purposes of this framework, it is important to distinguish between direct shading effects, thermal co-benefits, and non-shading co-benefits. Direct shading effects refer to the interception of solar radiation by foliage, canopy, or vegetative structures. Thermal co-benefits include evapotranspiration, surface temperature reduction, local air temperature moderation, and microclimatic cooling. Non-shading co-benefits, such as biodiversity support, stormwater management, air quality improvement, and psychological well-being, are relevant for broader urban climate adaptation but are not the primary assessment domain of this shading framework.

Nature-based systems therefore contribute to overheating resilience through a combination of exposure reduction and sensitivity mitigation [60]. Their performance depends on plant species, canopy density, leaf morphology, seasonal behaviour, irrigation conditions, façade or street orientation, local climate, and maintenance [54–56,61]. Deciduous vegetation introduces an additional seasonal dimension: it can provide substantial solar protection in summer while allowing greater solar access in winter. This makes nature-based systems particularly relevant for the temporal dimension of adaptive capacity, although their performance may also be vulnerable to drought, heat stress, and long-term climate change.

4.2.3. Morphological Self-Shading Systems

Morphological self-shading refers to shading generated by the geometry, orientation, and spatial configuration of buildings and urban fabric, rather than by an added shading device. This category addresses an important gap in conventional shading classifications, since many effective shading effects in real design practice derive from architectural and urban form itself.

At the building scale, morphological self-shading includes recessed windows, deep reveals, balconies, loggias, projecting slabs, façade articulation, overhangs integrated into massing, courtyards, and stepped or articulated building volumes. These elements reduce direct solar exposure through geometric obstruction and can influence the solar gains received by transparent and opaque envelope components.

At the urban scale, morphological self-shading includes arcades, porticoes, colonnades, continuous street walls, street-canyon geometry, height-to-width ratio, street orientation, courtyards, and building-to-building mutual shading. These configurations affect the amount of solar radiation reaching pedestrian spaces and urban surfaces, modifying sky exposure, mean radiant temperature, surface heating, and outdoor thermal comfort.

Morphological self-shading is generally static in temporal behaviour, because it is embedded in the physical configuration of the built environment. However, its performance varies over time as a function of solar geometry, season, latitude, and time of day. In resilience terms, it primarily contributes to exposure reduction, while indirectly supporting sensitivity mitigation by reducing the thermal load imposed on buildings, surfaces, and pedestrians. Because morphological self-shading is not an add-on technology, it is particularly relevant for early-stage design, urban planning, and retrofit strategies based on spatial configuration.

4.2.4. Hybrid Shading Systems

Hybrid shading systems combine two or more physical mechanisms of solar control. They may integrate artificial structures with vegetation, combine morphological shading with green infrastructure, or incorporate adaptive technological components into nature-based or architectural systems. Examples include vegetated pergolas, green arcades, artificial structures supporting climbing plants, temporary urban shading systems used while

trees mature, adaptive vegetated canopies, and mixed systems combining textile shading, vegetation, and urban furniture [54,62–64].

Hybrid systems are particularly relevant to overheating resilience because they can combine the immediate effectiveness of artificial shading with the seasonal and ecological benefits of vegetation. For example, an artificial pergola can provide a fixed support structure, while deciduous vegetation introduces seasonal variation in solar access. Similarly, temporary artificial shading can reduce heat exposure in the short term while longer-term tree canopy develops. In this sense, hybrid systems may contribute simultaneously to exposure reduction, sensitivity mitigation, and adaptive capacity enhancement.

4.3. Temporal Behaviour of Shading Systems

In addition to their physical mechanism, shading systems can be classified according to their temporal behaviour. This dimension cuts across artificial, nature-based, morphological, and hybrid categories.

Static or fixed systems maintain a stable configuration over time. Examples include fixed overhangs, vertical fins, brise-soleil, light shelves, recessed windows, loggias, arcades, porticoes, and street-canyon self-shading. Their performance depends on geometry, orientation, latitude, and seasonal solar trajectories. Although they lack real-time responsiveness, they offer robustness, operational continuity, low maintenance, and low technical vulnerability.

Dynamic or operable systems can be moved, adjusted, opened, closed, deployed, or reconfigured. Examples include venetian blinds, movable louvers, sliding panels, retractable shade sails, operable screens, and temporary urban shading structures. These systems allow more flexible control of solar exposure, but their performance depends on user behaviour, control logic, mechanical reliability, and maintenance.

Seasonal or ecological systems change primarily through biological or seasonal processes. Examples include deciduous street trees, green façades, climbing plants, vegetated pergolas, and seasonal canopy structures. Their shading performance varies with leaf area, canopy density, growth stage, pruning, irrigation, and climatic stress. These systems are especially relevant for balancing summer solar protection with winter solar access.

Adaptive or responsive systems modify their performance in response to environmental conditions, control inputs, or material behaviour. Examples include automated blinds, sensor-controlled louvers, adaptive façades, chromogenic glazing, kinetic shading devices, smart-material systems, and hybrid systems with active management. These systems contribute directly to adaptive capacity because they can modulate shading performance across diurnal variability, heatwaves, and changing climatic conditions.

4.4. Multidimensional Classification and Implications for KPI Selection

Figure 6 illustrates the proposed two-axis classification of shading systems. The horizontal axis represents the physical mechanism of shading, distinguishing artificial or technological, nature-based, morphological self-shading, and hybrid systems. The vertical axis represents temporal behaviour, distinguishing static, dynamic or operable, seasonal or ecological, and adaptive or responsive systems. This structure avoids treating categories such as static, adaptive, and nature-based as mutually exclusive and instead allows each shading solution to be positioned according to both its material or spatial mechanism and its mode of temporal operation.

The multidimensional classification has direct implications for KPI selection. Artificial static systems require indicators related to geometric solar obstruction and solar radiation control. Artificial dynamic or adaptive systems require additional indicators describing modulation range, response time, and control flexibility. Nature-based systems require indicators that capture vegetation structure, canopy density, seasonal variation, and thermal

co-benefits. Morphological self-shading requires indicators related to solar access, sky exposure, façade or street geometry, and shaded surface or pedestrian area. Hybrid systems require combined indicators able to capture both physical shading performance and seasonal or adaptive behaviour.

Table 1 synthesises the proposed classification by linking scale, physical mechanism, temporal behaviour, examples, resilience contribution, and methodological implications for KPI structuring.

Table 1. Multidimensional classification of shading systems and implications for KPI structuring.

Scale	Physical Mechanism	Temporal Behaviour	Examples	Primary Contribution to Overheating Resilience	Methodological Implications for KPI Structuring
Building	Artificial/technological	Static/fixed	Fixed overhangs, vertical fins, brise-soleil, light shelves, fixed screens	Exposure reduction; indirect sensitivity mitigation	Indicators related to geometric obstruction, solar transmittance, shading factor, and cooling-load response
Building	Artificial/technological	Dynamic/adaptive	Venetian blinds, movable louvers, sliding panels, adaptive façade, chromogenic systems	Exposure reduction and adaptive capacity enhancement	Indicators related to modulation range, actuator response time, control strategy, SHGC variation, and overheating response
Building	Nature-based/vegetative	Seasonal/ecological	Green façade, living walls, climbing plants, vegetated screens	Exposure reduction, sensitivity mitigation, seasonal adaptive capacity	Indicators related to vegetation coverage, LAI, seasonal variation, surface temperature reduction, and thermal response
Building	Morphological self-shading	Static/fixed	Recessed windows, deep reveals, balconies, loggias, courtyards, façade articulation	Exposure reduction; indirect sensitivity mitigation	Indicators related to façade geometry, shaded façade ratio, projection factor, solar access, and indoor thermal response
Urban	Artificial/technological	Static/dynamic	Shade sails, canopies, shelters, textile shading, urban pergolas	Exposure reduction and outdoor sensitivity mitigation	Indicators related to shaded area, radiative flux attenuation, mean radiant temperature, and outdoor comfort
Urban	Nature-based/vegetative	Seasonal/ecological	Street trees, urban forests, parks, hedges, vegetative barriers	Exposure reduction, sensitivity mitigation, long-term adaptive capacity	Indicators related to canopy coverage, LAI, seasonal canopy variation, air temperature, surface temperature, and outdoor comfort
Urban	Morphological self-shading	Static/fixed	Arcades, porticoes, colonnades, street-canyon geometry, H/W ratio, street orientation, mutual building shading	Exposure reduction and outdoor sensitivity mitigation	Indicators related to SVF, solar access, shaded pedestrian area, MRT, and urban geometry
Multiscale	Hybrid	Seasonal/adaptive	Vegetated pergolas, green arcades, temporary shading while trees mature, artificial structures with vegetation	Combined exposure reduction, sensitivity mitigation, and adaptive capacity enhancement	Multi-domain indicators combining radiative control, thermal response, seasonal variation, and adaptive performance

The proposed classification does not assign each shading solution to a single fixed category. Instead, each solution is positioned according to its scale of application, physical mechanism, temporal behaviour, and primary contribution to overheating resilience. This multidimensional structure provides the basis for KPI selection, since different mechanisms and temporal behaviours require different indicators, baselines, and calibration procedures. It also clarifies the relationship between building and urban shading: the two scales are not alternative domains, but complementary levels through which overheating risk can be reduced by controlling solar-radiative exposure, moderating thermal response, and enhancing adaptive capacity across time.

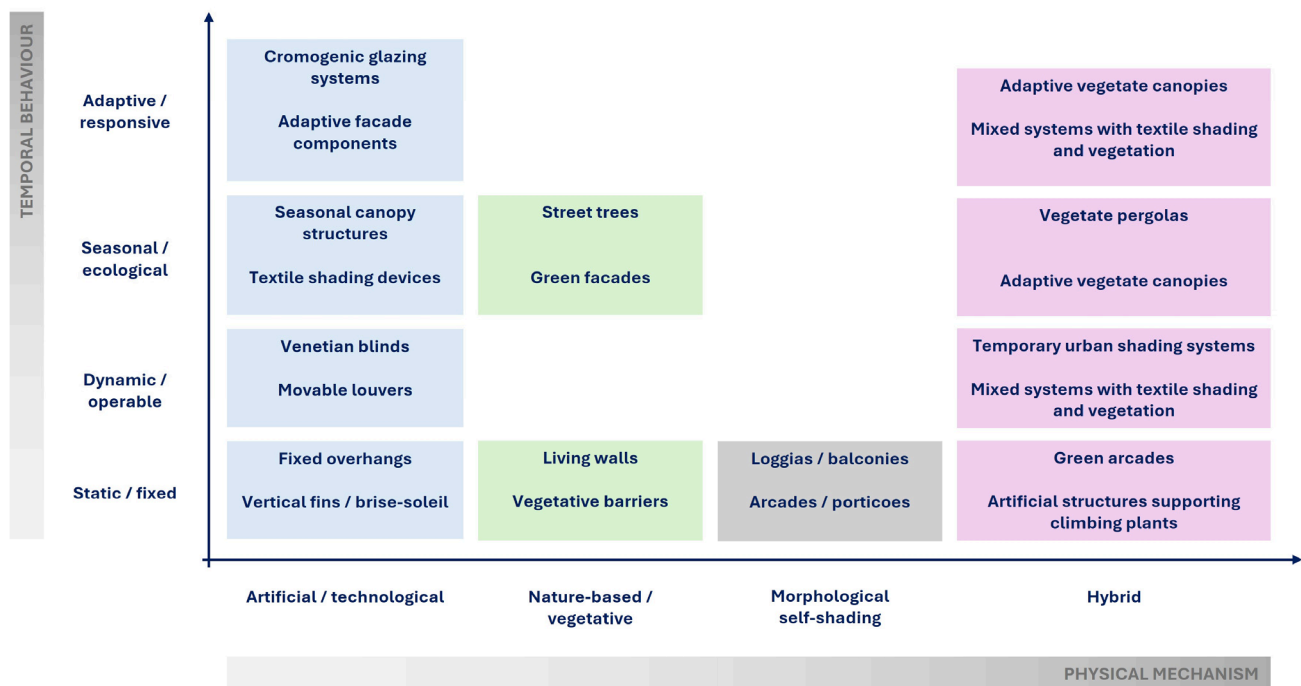


Figure 6. Two-axis classification of shading systems according to physical mechanism and temporal behaviour.

5. KPI Framework for Overheating-Resilient Shading

The KPI framework translates the multidimensional classification of shading systems into a structured set of performance indicators applicable across building and urban scales. KPIs are organised according to the three analytical dimensions adopted in this study: exposure reduction, sensitivity mitigation, and adaptive capacity enhancement. This structure links the physical mechanisms and temporal behaviour of shading systems to measurable performance outcomes while preserving the distinction between climate-invariant KPI definitions and climate-sensitive assessment conditions.

The framework is organised into three complementary KPI domains:

- exposure, describing the control of solar-radiative input before thermal effects occur;
- sensitivity, describing the resulting thermal and comfort response;
- adaptive capacity, describing the ability of shading systems to modulate or maintain performance over time under variable conditions.

5.1. KPI Assignment by Resilience Dimensions

KPIs are primarily associated with one of the three analytical dimensions adopted in this study: exposure reduction, sensitivity mitigation, or adaptive capacity enhancement.

Exposure-related KPIs describe the radiative input to the system before it produces thermal effects. At the building scale, these include indicators such as Solar Heat Gain Coefficient [65–67], Shading Factor [68,69], Solar Transmittance [70,71], and Projection Factor [72]. At the urban scale, exposure is described through indicators such as Sky View Factor [73,74], Urban Tree Canopy Coverage [75–77], and Leaf Area Index [78,79], which capture solar access, canopy interception, and vegetation-based radiative shielding.

Sensitivity-related KPIs describe the thermal response of indoor or outdoor environments after radiative loads have affected the system. At the building scale, these include operative temperature reduction, Overheating Degree Hours [80,81], Exceedance Hours, cooling demand indicators, and surface temperature decrease [82–86]. At the urban scale,

they include Mean Radiant Temperature reduction [87–90], air temperature variation at pedestrian level [91], surface temperature decrease [92], UTCI, and PET [93–97].

Adaptive-capacity KPIs describe the ability of shading systems to modify their performance over time. At the building scale, this includes Modulation Range [37,42,43], Actuator Response Time [37,43,98,99], Seasonal Reversibility [43,45,100], and seasonal LAI variation for vegetation-based systems [101,102]. At the urban scale, adaptive capacity is represented by Seasonal Canopy Variability [103], flexibility of temporary shading structures, and Vegetation Growth Performance under Climate Stress [104].

Since some indicators capture more than one mechanism, the framework distinguishes between the primary resilience dimension of each KPI and its secondary relevance. For example, Mean Radiant Temperature is primarily interpreted as a sensitivity-related KPI, but it also reflects changes in radiative exposure. Similarly, LAI can describe exposure reduction when used to characterize canopy density, while Δ LAI expresses adaptive capacity when used to assess seasonal variation.

5.2. KPI Applicability by Shading Typology and Scale

The revised classification of shading systems affects KPI selection because not all indicators are applicable to all shading typologies. For this reason, the framework links each KPI to the shading mechanisms for which it is most relevant.

For artificial and technological systems, such as overhangs, fins, brise-soleil, venetian blinds, movable louvers, chromogenic systems, and adaptive facade components, relevant KPIs include geometric and radiative indicators such as Projection Factor, Shading Factor, Solar Transmittance, SHGC, and radiative attenuation. When these systems are dynamic or adaptive, indicators such as Modulation Range, Actuator Response Time, control strategy type, and Seasonal Reversibility become relevant.

For nature-based and vegetative systems, such as street trees, green facades, living walls, climbing plants, vegetated pergolas, and vegetative barriers, relevant KPIs include Urban Tree Canopy Coverage, LAI, Δ LAI, Seasonal Canopy Variability, surface temperature decrease, MRT reduction, and outdoor comfort indicators such as UTCI and PET.

For morphological self-shading systems, such as recessed windows, loggias, balconies, arcades, porticoes, street-canyon geometry, and mutual shading between buildings, relevant KPIs include Projection Factor, Sky View Factor, shaded area ratio, solar access indicators, MRT reduction, and outdoor comfort response. These indicators are particularly important where shading is generated by geometry rather than by an added device.

For hybrid systems, such as vegetated pergolas, green arcades, temporary shading combined with vegetation, or artificial structures supporting climbing plants, KPI selection combines radiative, thermal, vegetative, and temporal indicators. These systems may require both exposure-related indicators, such as shaded area or canopy coverage, and adaptive-capacity indicators, such as seasonal canopy variability or flexibility of reconfigurable shading structures.

5.3. Climate Dependency and Calibration Requirements

The framework also distinguishes between climate-invariant KPI definitions and climate-sensitive assessments. This distinction does not imply that some KPIs are independent of climate. Rather, it clarifies whether the KPI is transferable mainly at the level of definition or whether its assessment requires local calibration.

KPIs such as SHGC, Shading Factor, Solar Transmittance, Projection Factor, Sky View Factor, canopy coverage, and LAI have relatively stable operational definitions. However, their target values and design interpretation vary with climate, latitude, season, solar

geometry, and overheating risk. They are therefore treated as climate-invariant in definition, but not climate-independent.

By contrast, KPIs such as operative temperature reduction, Overheating Degree Hours, cooling load variation, surface temperature decrease, MRT, UTCI, PET, and vegetation growth performance under climate stress require explicit calibration of climatic inputs, base-line scenarios, evaluation periods, comfort thresholds, and local microclimatic conditions. These are treated as climate-sensitive assessments.

Calibration requirements are therefore included in the operational matrix. Low calibration indicates that the KPI is mainly based on a stable technical or geometric definition. Medium calibration indicates that the KPI definition is stable, but interpretation depends strongly on climate, latitude, season, or morphology. High calibration indicates that both assessment conditions and interpretation must be locally defined before cross-climate comparison.

5.3.1. Building-Scale KPI Structuring

At the building scale, exposure-related KPIs are facade-oriented and geometry-dependent. State-of-the-art research identifies shading factor, Solar Heat Gain Coefficient (SHGC), incident solar radiation attenuation, and effective shading ratio as robust measures of radiative control at the envelope level. These indicators are strongly conditioned by facade orientation, latitude, and seasonal solar geometry, and are substantially climate-invariant in their definition, though their target values differ across climatic and latitudinal contexts.

Sensitivity-related KPIs at the building scale address the indoor thermal response to solar load reduction. Current evidence highlights operative temperature reduction, cooling load variation, peak cooling demand, and surface temperature decrease as relevant indicators of overheating mitigation. Resilient cooling literature further emphasises the evaluation of thermal comfort degradation during extreme heat events—through indicators such as Overheating Degree Hours (ODH) and Exceedance Hours above locally defined thresholds—rather than relying solely on seasonal energy consumption metrics.

Adaptive capacity-related KPIs at the building scale reflect the dynamic performance of shading systems across variable conditions. In the context of adaptive facades and smart materials, relevant indicators include modulation range, actuator response time, control strategy type (manual, automated, or intrinsic material response), and seasonal reversibility. These indicators capture the ability of systems to adjust to diurnal variability and heatwave conditions, which is central to contemporary climate resilience thinking. For nature-based systems, Leaf Area Index seasonal variation (ΔLAI) constitutes the ecological equivalent, directly conditioning the transmitted radiation differential between summer and winter configurations.

5.3.2. Urban-Scale KPI Structuring

At the urban scale, exposure-related KPIs shift from facade-level metrics to spatial and morphological indicators. Urban tree canopy coverage, shaded area ratio, Sky View Factor (SVF) modification, and radiative flux attenuation at pedestrian level are widely adopted in recent microclimate studies to quantify exposure reduction in outdoor environments. These indicators are particularly relevant in high-density contexts where shading performance is conditioned by urban geometry and surface albedo interactions.

Sensitivity-related KPIs address the thermal response of outdoor environments to shading interventions. The most robust and widely adopted indicators in recent evidence include Mean Radiant Temperature (MRT) reduction, air temperature variation at pedestrian level, surface temperature decrease, and changes in composite thermal comfort indices such as the Universal Thermal Climate Index (UTCI) and Physiologically Equivalent Temperature (PET). These parameters directly reflect the mitigation of outdoor heat stress and are increasingly integrated into climate adaptation planning and urban design guidelines.

Adaptive capacity-related KPIs at the urban scale are linked to seasonal variability, ecological growth dynamics, and configurational flexibility of shading infrastructures. Contemporary research on nature-based solutions and hybrid shading systems identifies seasonal canopy variability, vegetation growth performance under climate stress, and the flexibility of temporary or reconfigurable shading structures as relevant indicators. These KPIs capture the long-term and evolutionary dimension of climate resilience in urban systems, including the multifunctional integration of shading with stormwater management and evaporative cooling functions.

5.4. Exposure KPIs Matrix

The exposure matrix groups indicators that describe radiative input before it produces a thermal effect on the building or urban environment. At the building scale, exposure-related KPIs include Solar Heat Gain Coefficient (SHGC) [65–67], Shading Factor (SF) [68,69], Solar Transmittance (τ_{sol}) [70,71], and Projection Factor (PF) [72], which collectively characterize solar transmission, shading effectiveness, and geometric solar obstruction at the envelope level. At the urban scale, exposure is represented by Sky View Factor (SVF) [73,74], Urban Tree Canopy Coverage [75–77], and Leaf Area Index (LAI) [78,79], which describe solar access, canopy interception, and vegetation-based radiative shielding in outdoor environments. Most exposure indicators are climate-invariant in formulation, since they are defined through geometric or physical quantities that remain stable across climatic contexts. Their interpretation, however, remains climate-dependent, because the desirability of solar exclusion varies with latitude, season, and overheating risk. The matrix therefore distinguishes between universal metric definition and context-specific design relevance, providing a consistent basis for cross-context comparison without suppressing climatic specificity.

5.5. Sensitivity KPIs Matrix

The sensitivity matrix groups indicators that measure the thermal response of indoor and outdoor environments after radiative loads have already affected the system. At the building scale, this includes operative temperature reduction (ΔT_o) [84], Overheating Degree Hours (ODH) [80,81], Exceedance Hours, Peak Cooling Demand reduction (ΔPCL), Cooling Load Variation (ΔCL) [85,86], and Surface Temperature decrease (ΔT_s) [82,83], which together describe thermal comfort response, overheating magnitude and duration, peak and cumulative cooling demand, and the thermal response of the building fabric.

At the urban scale, sensitivity KPIs capture the thermal response of outdoor environments through Mean Radiant Temperature reduction (ΔMRT) [87–90], Air Temper-

ature variation at pedestrian level (ΔT_a) [91], Surface Temperature decrease (ΔT_s) [92], and the composite indices UTCI and PET [93–97]. Within this set, ΔMRT and ΔT_a describe specific environmental responses, whereas UTCI and PET provide an integrated estimate of pedestrian thermal stress and perceived outdoor comfort. UTCI and PET are expressed in $^{\circ}C$ according to their conventional reporting units, but these values represent equivalent-temperature indices rather than direct air-temperature measurements. Their interpretation depends on the underlying meteorological variables, human parameters, and assessment conditions.

All sensitivity indicators are climate-sensitive, since their interpretation depends on locally meaningful thresholds for comfort, overheating, and physiological stress. Their value within the matrix therefore lies not only in documenting thermal response, but also in clarifying which comparisons across studies require explicit climatic calibration before interpretation. In this sense, the matrix strengthens methodological comparability while preserving the climatic specificity required for resilience-oriented assessment.

5.6. Adaptive Capacity KPIs Matrix

The adaptive-capacity matrix groups indicators that express the ability of shading systems to modify their performance over time in response to variable or extreme climatic conditions. Unlike the previous two matrices, this set is explicitly structured by temporal scale, distinguishing between diurnal, seasonal, and long-term adaptive behaviour. At the building scale, the most relevant indicators include Modulation Range [37,42,43], Actuator Response Time (ART) [37,43,98,99], Seasonal Reversibility [43,45,100], and ΔLAI [101,102], which capture dynamic solar control, speed of response, seasonal reconfigurability, and ecological adaptation in vegetation-based systems.

At the urban scale, adaptive capacity is represented by Seasonal Canopy Variability [103], Flexibility of temporary shading structures, and Vegetation Growth Performance under Climate Stress [104], which describe seasonal canopy dynamics, infrastructural reconfigurability, and the long-term persistence of shading performance under future heat and drought stress. These indicators extend adaptive capacity beyond short-term adjustability and connect it to ecological resilience and long-term climate responsiveness.

Most adaptive-capacity indicators are climate-invariant in formulation at the diurnal and seasonal scales, since they are based on physically or functionally defined properties of system adjustment. By contrast, long-term adaptive-capacity indicators are climate-sensitive, because their interpretation depends on projected climatic trajectories and local ecological stress thresholds. The adaptive-capacity matrix therefore introduces a temporal and forward-looking dimension that is largely absent from conventional shading assessment approaches.

5.7. Multiscale KPI Matrix

The matrix (Table 2) summarises the resulting KPI framework. Each indicator is mapped according to its application scale, applicable shading typologies, primary resilience dimension, secondary relevance, unit of measurement, climate dependency, calibration requirement, and temporal scale where relevant. The matrix therefore provides an operational bridge between the classification of shading systems and the selection of KPIs for future empirical, simulation-based, or comparative studies.

Table 2. Multiscale KPI matrix for overheating-resilient shading solutions in the built environment.

KPI	Scale	Applicable Typologies	Primary Dimension	Secondary Relevance	Unit	Climate Dependency	Calibration Requirement	Main Calibration Factors / Temporal Scale
EXPOSURE—radiative input before thermal effect								
Solar Heat Gain Coefficient (SHGC)	Building	Artificial/technological envelope systems; adaptive façade; glazing-integrated systems	Exposure	Sensitivity	0–1	Climate-invariant	Medium	Orientation; solar geometry; seasonal target values
Shading Factor (SF)	Building	Fixed, dynamic, and adaptive artificial shading; hybrid façade systems	Exposure	Sensitivity	0–1	Climate-invariant	Medium	Orientation; latitude; reference unshaded condition
Solar Transmittance (τ_{sol})	Building	Glazing, screens, textiles, louvers, adaptive materials	Exposure	Sensitivity	0–1	Climate-invariant	Medium	Solar spectrum; incidence angle; seasonal target values
Projection Factor (PF)	Building	Overhangs, fins, brise-soleil, recessed windows, morphological façade shading	Exposure	Sensitivity	ratio	Climate-invariant	Medium	Latitude; orientation; seasonal solar geometry
Sky View Factor (SVF)	Urban	Morphological self-shading; street canyons; arcades; tree canopy configurations	Exposure	Sensitivity	0–1	Climate-invariant	Medium	Urban geometry; H/W ratio; orientation; sky exposure
Urban Tree Canopy Coverage	Urban	Nature-based and hybrid urban shading systems	Exposure	Sensitivity	%	Climate-invariant	Medium	Canopy geometry; species; season; maintenance
Leaf Area Index (LAI)	Building/Urban	Green façade, living walls, street trees, vegetated pergolas	Exposure	Adaptive capacity	m ² /m ²	Climate-invariant	Medium	Species; canopy density; phenology; irrigation
SENSITIVITY—thermal response to residual radiative loads								
Operative Temperature reduction (ΔT_o)	Building	All building-scale shading typologies	Sensitivity	Exposure	°C	Climate-sensitive	High	Weather file; occupancy; comfort model; baseline
Overheating Degree Hours (ODH)	Building	All building-scale shading typologies	Sensitivity	Adaptive capacity during heat events	°C h/yr	Climate-sensitive	High	Threshold; evaluation period; heatwave scenario
Peak Cooling Demand reduction (ΔPCL)	Building	All building-scale shading typologies affecting solar gains	Sensitivity	Exposure	W/m ²	Climate-sensitive	High	Weather file; internal gains; HVAC assumptions; baseline

Table 2. Cont.

KPI	Scale	Applicable Typologies	Primary Dimension	Secondary Relevance	Unit	Climate Dependency	Calibration Requirement	Main Calibration Factors/ Temporal Scale
Cooling Load Variation (Δ CL)	Building	All building-scale shading typologies affecting cooling demand	Sensitivity	Exposure	kWh/m ² /yr	Climate-sensitive	High	Weather file; simulation assumptions; setpoints; baseline
Exceedance Hours	Building	All building-scale shading typologies	Sensitivity	Adaptive capacity during extreme periods	h/yr	Climate-sensitive	High	Comfort threshold; occupancy schedule; heatwave period
Surface Temperature decrease (Δ Ts)	Building/Urban	Envelope shading; urban canopies; trees; morphological and hybrid shading	Sensitivity	Exposure	°C	Climate-sensitive	High	Material properties; solar exposure; wind; evapotranspiration; baseline
Mean Radiant Temperature reduction (Δ MRT)	Urban	Urban shading, trees, canopies, arcades, street-canyon self-shading	Sensitivity	Exposure	°C	Climate-sensitive	High	Radiation model; pedestrian height; sky view; wind; humidity
Air Temperature variation at pedestrian level (Δ Ta)	Urban	Nature-based, hybrid, and urban-scale artificial shading	Sensitivity	Microclimatic co-benefits	°C	Climate-sensitive	High	Weather conditions; ventilation; surface materials; measurement height
Universal Thermal Climate Index (UTCI)	Urban	Urban-scale shading affecting pedestrian heat stress	Sensitivity	Integrated comfort outcome	°C	Climate-sensitive	High	Meteorological inputs; exposure scenario; local stress thresholds
Physiologically Equivalent Temperature (PET)	Urban	Urban-scale shading affecting pedestrian comfort	Sensitivity	Integrated comfort outcome	°C	Climate-sensitive	High	Meteorological inputs; human parameters; comfort thresholds
ADAPTIVE CAPACITY—dynamic regulation over time								
Modulation Range	Building	Dynamic, operable, adaptive, and smart shading systems	Adaptive capacity	Exposure	Δ SHGC or %	Climate-invariant	Low/Medium	Control range; open/closed reference states; diurnal scale
Actuator Response Time (ART)	Building	Automated blinds, movable louvers, adaptive façade components	Adaptive capacity	Exposure	min/s	Climate-invariant	Low	Control signal; actuator type; diurnal scale

Table 2. Cont.

KPI	Scale	Applicable Typologies	Primary Dimension	Secondary Relevance	Unit	Climate Dependency	Calibration Requirement	Main Calibration Factors/ Temporal Scale
Seasonal Reversibility	Building	Adaptive façade, seasonal devices, reversible shading configurations	Adaptive capacity	Exposure	Δ SHGC or Δ SF	Climate-invariant	Medium	Summer/winter reference states; seasonal solar geometry
Delta LAI—Seasonal LAI Variation	Building/ Urban	Green façade, climbing plants, vegetated pergolas, street trees	Adaptive capacity	Exposure	m ² /m ²	Climate-invariant	Medium/High	Phenology; species; irrigation; seasonal period
Seasonal Canopy Variability	Urban	Street trees, urban forests, vegetated pergolas, hybrid green structures	Adaptive capacity	Exposure/ Sensitivity	Δ LAI/ Δ crown density	Climate-invariant	Medium/High	Canopy development; pruning; seasonal climate; maintenance
Flexibility of temporary shading structures	Urban	Temporary canopies, retractable sails, modular pergolas, reconfigurable shelters	Adaptive capacity	Exposure	categorical/ Δ coverage %	Climate-invariant	Medium	Deployment period; spatial coverage; seasonal use
Vegetation Growth Performance under Climate Stress	Urban	Nature-based and hybrid vegetative shading systems	Adaptive capacity	Exposure/ Sensitivity	Δ LAI or Δ canopy cover %/yr	Climate-sensitive	High	Projected heat and drought stress; irrigation; species resilience

6. Operational Workflow for KPI Selection and Interpretation

The proposed framework is operationalised through a stepwise workflow that guides the selection and interpretation of KPIs for overheating-resilient shading solutions, as shown in Figure 7. The workflow is intended to support comparative assessment across building and urban scales without assuming that all indicators are directly comparable across climatic contexts.

1. First, the assessment objective is defined by specifying whether the analysis focuses on radiative exposure reduction, indoor or outdoor thermal response, cooling-demand reduction, pedestrian comfort, or adaptive performance under variable climatic conditions. This step clarifies the dominant performance question and determines the relevant KPI domain.
2. Second, the spatial scale and shading typology are identified. The system is classified according to its application scale—building, urban, or multiscale—and according to the multidimensional classification introduced in Section 4: physical shading mechanism and temporal behaviour. This step determines which KPIs are applicable to the system under assessment.
3. Third, KPIs are selected from the multiscale matrix according to their primary resilience dimension and secondary relevance. Exposure KPIs are selected when the aim is to quantify solar-radiative input or shading effectiveness; sensitivity KPIs are selected when the aim is to assess thermal response, comfort, or cooling demand; adaptive-capacity KPIs are selected when temporal modulation, seasonal behaviour, or responsiveness is relevant.
4. Fourth, the climate dependency of each KPI is identified. Indicators with climate-invariant definitions can be transferred across contexts at the level of metric definition, although their targets and interpretation remain climate-dependent. Climate-sensitive assessments require local calibration before comparison, including climate inputs, baseline scenarios, evaluation periods, comfort thresholds, and microclimatic boundary conditions.
5. Finally, the results are interpreted according to the assessment context rather than as absolute performance values. The framework therefore supports KPI selection, comparison, and interpretation, but does not replace empirical monitoring, simulation-based evaluation, or context-specific performance validation.

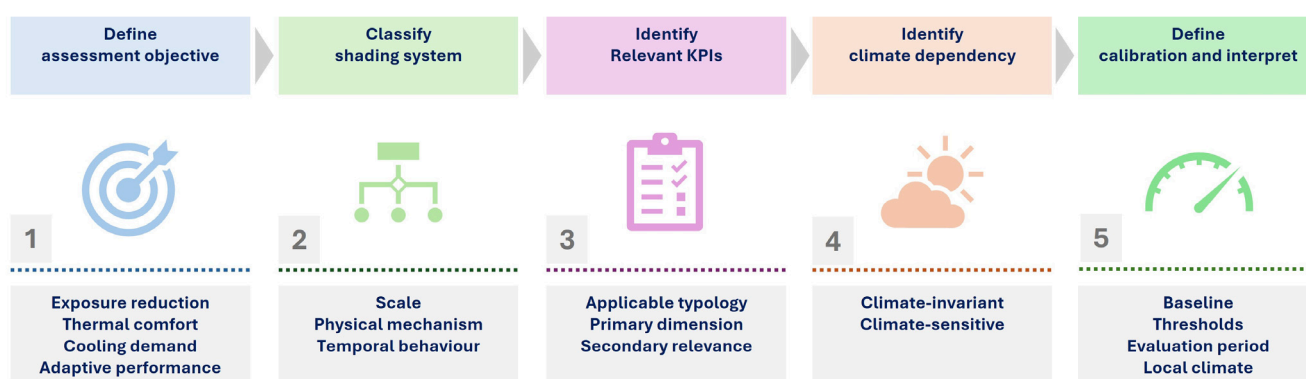


Figure 7. The Proposed KPI-Based Performance Framework for Climate-Resilient Shading Systems.

7. Results

Consistent with the evidence-based synthesis design, the results describe the distribution, comparability, and recurring performance patterns of the published evidence rather than estimating pooled causal effects. Results are organised in five parts, following the sequence for the quantitative synthesis: climate stratification of the sample, KPI-family

grouping, comparison of shading typologies, and separate synthesis of the resulting evidence families.

7.1. Climate Stratification

The Köppen–Geiger classifications recorded for each case were aggregated into four climate families, Tropical, Arid, Temperate, and Continental, to support group-level comparison. Table 3 reports the resulting distribution.

Table 3. Case distribution by climate family.

Climate Family	Climate Zone	Number of Cases	% of Sample
Temperate	Cfa, Csa, Cfb, Cwb	29	63%
Arid	BWh, BSk, BWk	13	28%
Continental	Dwa, Dwb/Dwa	3	7%
Tropical	Am	1	2%

Climate zone: Cfa—humid temperate climate, with no dry season and hot summers; Csa—Mediterranean climate, with hot, dry summers; Cfb—oceanic temperate climate, with no dry season and mild summers; Cwb—temperate climate with dry winters and mild summers; BWh—hot desert climate; BSk—cold semi-arid (steppe) climate; BWk—cold desert climate; Dwa—continental climate with dry winters and hot summers; Dwb—continental climate with dry winters and mild summers; Am—tropical monsoon climate.

The sample is markedly concentrated in temperate climates (29 cases, 63%), with substantial representation of arid climates (13 cases, 28%). Continental (3 cases) and, in particular, tropical climates (1 case, [105]) are sparsely represented. This imbalance is treated as a methodologically relevant finding in its own right rather than a limitation to be concealed: it indicates that the published, quantitatively comparable evidence base on shading-system performance is itself unevenly distributed across climate zones, with tropical and continental contexts remaining comparatively under-documented.

7.2. KPI-Family Grouping

The 46 case studies yielded 243 individual Case × KPI × Comparison rows. Table 4 summarises their distribution across the three KPI Family/Domain categories, and Table 5 reports the climate-transferability classification within each family.

Table 4. KPI rows and cases by KPI family.

KPI Family	n Rows (of 243)	Number of Cases
Thermal/Overheating	190 (78%)	38 (83%)
Visual/Daylighting	31 (13%)	9 (20%)
Energy	22 (9%)	9 (20%)

Table 5. Climate-transferability classification by KPI Family.

KPI Family	Definition Climate-Invariant	Interpretation Climate-Dependent
Thermal/Overheating (N = 190)	182 (96%)	182 (96%)
Visual/Daylighting (N = 31)	31 (100%)	31 (100%)
Energy (N = 22)	22 (100%)	17 (77%)

As shown in Table 6, across the database, sensitivity-mitigation indicators (55%) are the most frequent primary classification, followed by exposure-reduction indicators (37%) and adaptive-capacity indicators (9%). This distribution reflects the composition of the underlying evidence base: most reviewed studies report a thermal or visual response (e.g., a temperature or comfort-index reduction) rather than a purely geometric exposure metric or an explicitly time-resolved adaptive-capacity indicator, the latter requiring a dynamic or seasonally variable intervention to be meaningfully assessed. Adaptive-capacity classifications are concentrated in the subset of cases involving dynamic/operable or adaptive/responsive shading, consistent with the framework's structure; the Visual/Daylighting domain, in particular, contains no adaptive-capacity classifications, since none of the reported daylight or glare comparisons in the database evaluate a dynamic shading state against itself over time.

Table 6. Primary Resilience Dimension by KPI Family.

KPI Family	Exposure Reduction	Sensitivity Mitigation	Adaptive Capacity	Total
Thermal/Overheating	67	105	18	190
Visual/Daylighting	14	17	0	31
Energy	8	11	3	22
All rows (N = 243)	89	133	21	243

Within the recurring evidence families a small number of specific indicators account for a substantial share of the Thermal/Overheating domain, while wind speed and relative humidity function predominantly as explanatory covariates rather than standalone outcome measures, and 21 cases contribute indicators that are inherently case-specific (composite indices, correlation coefficients, or design recommendations) and are retained for narrative synthesis rather than pooled quantitative comparison.

7.3. Comparison of Shading Typologies

Figure 8 summarises the distribution of the 46 case studies across application scale, climate family, physical shading mechanism, and methodological approach.

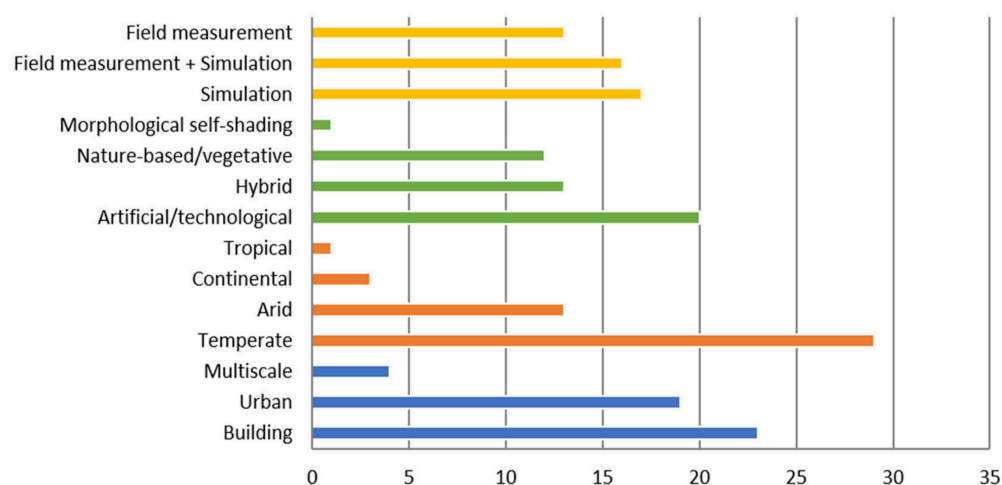


Figure 8. Distribution of the 46 case studies by application scale (blue), climate family (orange), physical shading mechanism (green), and methodological approach (yellow).

Building-scale interventions account for the largest share of the sample (23 cases, 50%), followed by urban-scale (19 cases, 41%) and multiscale/interface cases (4 cases, 9%). Regarding physical mechanisms, artificial/technological systems are the most frequent (20 cases), followed by hybrid configurations (13 cases) and nature-based/vegetative systems (12 cases); morphological self-shading is represented by a single case [106]. Static/fixed (19 cases) and seasonal/ecological (17 cases) temporal behaviours together account for the majority of the sample, while dynamic/operable (3 cases) and adaptive/responsive systems (7 cases) remain a smaller but methodologically distinct subset.

As shown in Table 7, artificial/technological systems are markedly concentrated at building scale (16 of 20 cases, 80%), consistent with their typical implementation as window- or facade-level devices, and are the only mechanism category represented across all four climate families. Hybrid systems, by contrast, are almost exclusively urban-scale (11 of 13 cases, 85%) and are absent from the tropical and continental subsets. Nature-based/vegetative systems are evenly split between building scale (5 cases), urban scale (5 cases), and multiscale/interface applications (2 cases), with interventions reported both as facade-integrated interventions [53,106–108] and as a freestanding urban-greening measure [54,109–113]. Given the limited tropical representation overall ($N = 1$), the absence of hybrid and nature-based systems from that subset is read as a gap in the currently available evidence rather than as a substantive finding about their applicability in tropical contexts.

Table 7. Physical shading mechanism by climate family and by application scale.

Mechanism	Climate Family				Application		
	Tropical	Arid	Temperate	Continental	Building	Urban	Multiscale
Artificial/technological	1	7	10	2	16	3	1
Hybrid	0	4	9	0	2	11	0
Nature-based/vegetative	0	2	9	1	5	5	2
Morphological self-shading	0	0	1	0	0	0	1

7.4. Separate Synthesis of Evidence Families

Air temperature, MRT, PET, and surface temperature each appear in 14–18 cases, providing a sufficiently populated basis for exploratory, climate-stratified descriptive synthesis (Table 8). Summary values are reported as case-level mean and maximum reduction, averaged separately over the cases reporting each statistic within each climate group, with separate denominators for means and maxima. These summaries describe patterns in the available evidence rather than pooled intervention effects or climate-specific causal effects. Given the limited tropical and continental representation, the synthesis for these four families is restricted to a two-group arid-versus-temperate comparison, except for MRT, for which one continental case is also reported.

Table 8. Recurring evidence families across the OASIS database, ranked by number of case studies.

Evidence Family/KPI	Number of Cases	KPI Rows
Air Temperature	18	24
Mean Radiant Temperature/Globe Temperature	14	18
PET/mPET	14	25

Table 8. *Cont.*

Evidence Family/KPI	Number of Cases	KPI Rows
Surface Temperature	14	23
Visual/Daylighting (sDA, UDI, DGP, ASE, etc.)	10	30
Solar Gains/Radiation	13	27
UTCI	7	8
Wind Speed	5	5
Cooling Energy/Load	6	12
Sky View Factor	4	5
Relative Humidity	4	4
Evapotranspiration/Latent Heat	3	7
Total Energy Consumption	3	4
Overheating/Discomfort Hours	6	8
Operative Temperature	1	1
Other case-specific indicators	21	42

7.4.1. Air Temperature (Outdoor/Pedestrian Level)

Air temperature was reported in 18 case studies; the outdoor/pedestrian-level synthesis is restricted to 14 cases reporting outdoor, pedestrian-level measurements, excluding indoor air-temperature outcomes (three cases) and a façade -gap microclimate measurement (one case) not directly comparable to ambient outdoor conditions. As reported in Table 9, case-level mean reductions averaged 1.92 °C in arid cases (N = 4 cases reporting a mean) and 1.18 °C in temperate cases (N = 8); maximum reductions averaged 3.88 °C in arid cases (N = 5) and 1.60 °C in temperate cases (N = 9). Two temperate cases show negligible or adverse effects on air temperature and are retained with their sign, and the arid mean is strongly influenced by a single hybrid case (5.89 °C; the arid mean without it is 0.60 °C). The case-level values also show substantial variability within both climate groups, indicating that the reported group averages should be interpreted as descriptive summaries rather than as representative effect magnitudes.

7.4.2. Mean Radiant Temperature

Mean radiant temperature was reported in 14 case studies across arid (4), temperate (9), and continental (1) climates; no tropical case reported this indicator. As reported in Table 10, across the available cases, case-level mean MRT reductions averaged 9.13 °C in temperate cases (N = 8); only two arid cases report a case-level mean (25.2 and 19.5 °C), which are therefore given individually without a group average. For the arid group, the available case-level mean reductions ranged from 19.5 to 25.2 °C, while the corresponding temperate values showed a broader range across cases. The case-level maximum reductions averaged 33.10 °C (arid, N = 4) and 10.79 °C (temperate, N = 9). One continental case reported a case-level mean reduction of 4.92 °C. These values illustrate substantial between-case variability and should therefore be interpreted as descriptive summaries of the available evidence rather than as pooled estimates of MRT reduction.

Table 9. Outdoor air temperature reduction by case and climate family. Note. Group averages include every row with a numeric value in the corresponding column (NR = excluded). Arid: mean 1.92 °C (n = 4; range 0.46–5.89 °C); maximum 3.88 °C (n = 5; range 1.20–6.08 °C). Temperate: mean 1.18 °C (n = 8; range −0.12 to 3.05 °C); maximum 1.60 °C (n = 9; range −0.20 to 5.10 °C).

Climate	Case	ΔT_a , Mean (°C)	ΔT_a , Max (°C)	Basis
Arid	[114]	−0.85	−1.20	shaded vs. unshaded sidewalks, daytime average
Arid	[115]	−5.89	−6.08	hybrid staggered shading + trees, best scenario
Arid	[112]	−0.49	−3.00	small park vs. sun-exposed rooftop;
Arid	[116]	NR	−4.10	urban prototype, single time point (17:00)
Arid	[117]	−0.46	−5.00	shading-material comparison, best material
Temperate	[118]	−1.75	−2.00	boulevard (tree-lined) vs. alley/arcade
Temperate	[119]	−0.86	−1.32	integrated greening, best of 5 pedestrian points
Temperate	[54]	−3.05	−5.10	green pergola vs. rope-only/unshaded control
Temperate	[120]	−1.80	−1.80	shade vs. sun, courtyard
Temperate	[52]	−0.75	−1.00	mature trees vs. current minimal vegetation
Temperate	[121]	~0.00	−1.60	green wall—bidirectional (−1.6 to +1.3 °C)
Temperate	[122]	NR	−0.26	shading-device material/size—negligible effect
Temperate	[109]	−1.37	−1.53	natural vs. artificial shading, housing estate
Temperate	[123]	+0.12	+0.20	greening vs. bare wall—null result

Table 10. MRT reduction by case and climate family. Note. Group averages include every row with a numeric value in the corresponding column (NR = excluded). Arid: mean not averaged (n = 2; 19.5 and 25.2 °C); maximum 33.10 °C (n = 4; range 28.3–40.1 °C). Temperate: mean 9.13 °C (n = 8; range 1.00–27.25 °C); maximum 10.79 °C (n = 9; range 1.92–35.0 °C). Continental: single case (mean 4.92 °C; maximum 7.70 °C), not averaged.

Climate	Case	ΔMRT , Mean (°C)	ΔMRT , Max (°C)	Basis
Arid	[114]	NR	−34.0	max. reported reduction, shaded vs. unshaded
Arid	[115]	−25.2	−28.3	hybrid staggered shading + trees, best scenario
Arid	[116]	NR	−40.1	daytime peak (16:00); +2 °C at night (reversal)
Arid	[117]	−19.5	−30.0	coverage-ratio scenarios S1–S5 (mean); S6, trees
Temperate	[124]	−5.78	−8.10	BEAV-10 scenario vs. non-built-up reference
Temperate	[118]	−14.0	−16.0	boulevard vs. alley/arcade
Temperate	[105]	NR	−4.7	best canyon geometry; wedge geometry +0.7 °C (E-W)
Temperate	[119]	−27.25	−35.0	4 of 5 points; 1 point +3.7 °C (radiation trap)
Temperate	[125]	−2.23	−2.23	single reported value
Temperate	[126]	−4.15	−6.30	optimised vs. reference awning
Temperate	[127]	−2.40	−3.20	PVC-coated tarp vs. no cover
Temperate	[121]	−1.00	−1.92	green wall, current-weather scenario
Temperate	[109]	−16.27	−19.65	best of 4 site × shading-type combinations
Continental	[128]	−4.92	−7.70	best/mean of 5 monitored squares, post-planting

7.4.3. Physiologically Equivalent Temperature

PET was reported in 14 case studies across arid (4) and temperate (10) climates. As reported in Table 11, case-level mean reductions averaged 13.70 °C in arid cases (range 5.7–17.4 °C, N = 4) and 6.22 °C in temperate cases (range 1.0–12.6 °C, N = 10); maximum reductions averaged 16.90 °C (arid, N = 4) and 8.67 °C (temperate, N = 10). The arid-group values are higher than the temperate-group values in this descriptive synthesis, although the substantial within-group ranges indicate considerable heterogeneity across cases. The relatively broad within-group ranges indicate substantial between-case heterogeneity, reinforcing the descriptive rather than inferential nature of these climate-group summaries. The higher descriptive average observed for the arid group is also apparent in the air-temperature and MRT summaries, but these cross-KPI patterns should not be interpreted as evidence of a common climate-specific effect.

Table 11. PET reduction by case and climate family. Note. Group averages include every row with a numeric value in the corresponding column (NR = excluded). Arid: mean 13.70 °C (n = 4; range 5.7–17.4 °C); maximum 16.90 °C (n = 4; range 13.0–18.6 °C). Temperate: mean 6.22 °C (n = 10; range 0.98–12.6 °C); maximum 8.67 °C (n = 10; range 1.51–14.4 °C).

Climate	Case	Δ PET, Mean (°C)	Δ PET, Max (°C)	Basis
Arid	[114]	−15.7	−17.6	shaded vs. unshaded canyon points
Arid	[127]	−17.4	−18.6	hybrid staggered shading + trees
Arid	[115]	−16.0	−18.4	best of 2 monitored public spaces
Arid	[117]	−5.7	−13.0	coverage-ratio scenarios (mean of S2–S5; S6, trees)
Temperate	[124]	−0.98	−1.70	BEAV-10 vs. non-built-up reference
Temperate	[118]	−9.5	−14.0	boulevard vs. alley/arcade (max PET)
Temperate	[119]	−7.5	−14.4	integrated greening scenario
Temperate	[120]	−12.6	−12.6	shade vs. sun, courtyard
Temperate	[126]	−1.8	−11.2	optimised vs. reference awning
Temperate	[127]	−1.45	−2.00	PVC-coated tarp vs. no cover
Temperate	[129]	−1.51	−1.51	comfort-optimised vs. planned pedestrian route
Temperate	[113]	−5.5	−5.5	100% vs. 0% canopy cover
Temperate	[122]	−12.0	−12.0	opaque shading material vs. no shading
Temperate	[109]	−9.34	−11.77	best of 4 site × shading-type combinations

7.4.4. Surface Temperature

Surface temperature was reported in 14 cases; the synthesis retains the 13 cases with a shaded-versus-unshaded (or vegetated-versus-bare) reference, across arid (4) and temperate (9) climates, and excludes one case whose reference is an existing shade sail. As reported in Table 12, case-level mean reductions averaged 5.74 °C in arid cases (N = 4) and 8.47 °C in temperate cases (N = 9); maximum reductions averaged 7.40 °C (Arid, N = 4) and 11.66 °C (temperate, N = 9)—the only one of the four families in which the temperate group shows a higher average reduction than the arid group. This difference coincides with differences in the surfaces measured across climate groups, with the arid subset including building envelopes and the temperate subset including several paved ground surfaces under vegetation canopy [109,130]. The case-level values also show substantial variation within the climate groups, indicating that these averages should be interpreted as

descriptive summaries of the available cases rather than as generalised climate-specific effects. Accordingly, the difference should not be interpreted as evidence of a climate-specific effect.

Table 12. Surface temperature reduction by case and climate family. Note. Group averages include every row with a numeric value in the corresponding column (NR = excluded). Arid: mean 5.74 °C (n = 4; range 1.7–7.7 °C); maximum 7.40 °C (n = 4; range 1.7–11.0 °C). Temperate: mean 8.47 °C (n = 9; range 0.97–15.3 °C); maximum 11.66 °C (n = 9; range 1.75–19.0 °C).

Climate	Case	ΔT_s , Mean (°C)	ΔT_s , Max (°C)	Basis
Arid	[82]	−7.7	−7.7	sunny vs. shaded surface
Arid	[115]	−5.98	−9.20	facade/roof, best of 4 orientation × scenario combos
Arid	[112]	−1.7	−1.7	land surface temperature, park vs. rooftop
Arid	[131]	−7.59	−11.0	exterior wall, green wall vs. bare wall
Temperate	[124]	−0.97	−1.75	BEAV-10 vs. non-built-up reference
Temperate	[105]	−3.65	−8.5	wall surface; pavement (pixelated, N-S) +1.1 °C
Temperate	[54]	−5.3	−5.3	thermal imaging, west orientation, peak hour
Temperate	[120]	−15.3	−15.3	shade vs. sun, all surfaces
Temperate	[55]	−10.0	−12.0	vegetated/paved areas, final scenario
Temperate	[110]	−10.45	−11.6	greened vs. non-greened wall, best system
Temperate	[130]	−13.5	−16.0	pavement cooling due to sun sails
Temperate	[111]	−19.0	−19.0	max. surface-temperature reduction, all materials
Temperate	[123]	−2.93	−15.5	exterior wall, 3 greening systems

Figure 9 summarises these case-level mean and maximum reductions across the four thermal evidence families for direct visual comparison.

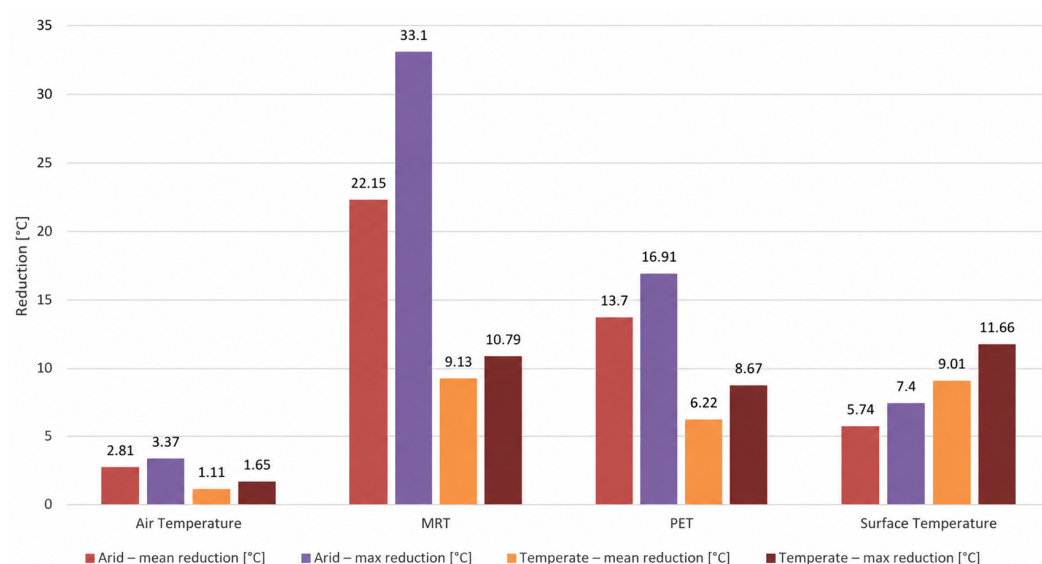


Figure 9. Case-level reduction by climate family across four thermal KPI families.

7.4.5. Visual/Daylighting Indicators

Visual/Daylighting indicators (spatial Daylight Autonomy, sDA; Useful Daylight Illuminance, UDI; Exceeded Useful Daylight Illuminance, EUDI; Daylight Glare Probability, DGP; Annual Sunlight Exposure, ASE) reported in 10 cases (nine classified under the Vi-

sual/Daylighting family in Table 4, plus the indoor illuminance indicator of Case 46). Unlike the four thermal families above, this evidence family is concentrated almost exclusively in building-scale, artificial/technological shading systems (Cases 7, 11, 12, 13, 25, 28, 30, 31), with a single urban-scale (Case 36) and a single nature-based (Case 46) exception and notably includes the database's only tropical case (Case 30). Given the heterogeneity of units (percentage of floor area, percentage of annual hours, glare-probability score) and the frequent use of relative rather than absolute comparisons between shading configurations, a climate-stratified numerical synthesis analogous to Tables 9–12 was not considered appropriate for this family.

7.5. Evidence Synthesis Across Climates and Shading Typologies

Beyond the climate-stratified comparison of individual KPIs, the database allows recurring associations between physical mechanism, application scale, and KPI family to be identified across the sample as a whole.

Artificial/technological systems are markedly concentrated at building scale (16 of 20 cases, 80%), consistent with their typical implementation as window- or facade-level devices. Hybrid systems, by contrast, are almost exclusively urban-scale (11 of 13 cases, 85%), reflecting their characteristic combination of built shading elements (canyons, arcades, canopies) with street trees at the neighbourhood or block level. Nature-based/vegetative systems are more evenly distributed between building scale (5 cases), urban scale (5 cases), and multiscale/interface applications (2 cases), indicating that vegetation-based shading is applied comparably often as a facade-integrated intervention and as a freestanding urban-greening measure.

Cross-referencing Table 3 with the mechanism x climate distribution indicates that artificial/technological systems are the only mechanism category represented across all four climate families, including the sample's sole tropical [105] case and two building-scale cases in the continental climate family. Hybrid and nature-based systems, conversely, are concentrated in temperate and arid climates and entirely absent from the tropical subset, a pattern that—given the limited tropical representation overall ($N = 1$)—should be read as a gap in the currently available evidence rather than as a substantive finding about the applicability of vegetative shading in tropical contexts.

The concentration of Visual/Daylighting indicators in artificial/technological, building-scale, and predominantly dynamic/adaptive systems further indicates that the trade-off between shading and daylight availability is evaluated in the reviewed literature primarily for kinetic and biomimetic facade systems, rather than for static shading devices or vegetation-based systems, for which visual performance is rarely reported alongside thermal performance in the same study.

8. Discussion

The proposed framework addresses a fragmentation that recurs throughout the shading literature reviewed in this study. Individual investigations have demonstrated, in isolation, the cooling potential of fixed and adaptive shading devices at the building scale [132], of urban-canyon geometry and facade articulation at the neighbourhood scale [133] and of vegetative systems such as green facades and vertical greenery [134–136], yet these contributions remain confined to single scales, single typologies, or single climatic contexts. Existing classification schemes for solar shading generally organise solutions according to morphological or technological criteria, such as fixed versus dynamic systems or building- versus urban-scale interventions [16,21]. While descriptively useful, such classifications do not establish a shared performance logic linking shading typology to measurable overheating-resilience outcomes. The multidimensional classification adopted in

this study—combining application scale, physical shading mechanism, temporal behaviour, and resilience contribution—and its translation into a KPI architecture spanning building and urban scales, responds directly to this gap and to the first three research questions guiding the study.

The distinction between exposure and sensitivity adopted throughout the framework is analytically necessary because radiative input and thermal response do not always covary. Direct comparisons between natural and artificial shading report divergent cooling efficacy depending on the receiving surface and climatic conditions [137], while urban morphological interventions that reduce mean radiant temperature at street level do not necessarily produce proportional reductions in cooling load at the building scale [133]. The finding that MRT and PET showed the most consistent directional responses across climates in the assembled database, whereas outdoor air temperature was comparatively insensitive to localised shading, reinforces this separation empirically: aggregate exposure reduction does not translate uniformly into sensitivity mitigation across all thermal metrics.

Among prior contributions, the Outdoor Shading Assessment Method proposed by Elrefai and Nikolopoulou [15] comes closest to the present framework, using UTCI to show that shading benefits are climate-dependent—advantageous under hot-arid conditions but potentially counterproductive where winter solar gains remain desirable. OSAM, however, remains confined to the outdoor urban scale and does not integrate building-level indicators or a structured criterion for identifying which KPIs require local calibration. The present framework extends this logic in two respects: it proposes an author-defined operationalisation of an exposure–sensitivity–adaptive capacity structure informed by the IPCC climate-risk and vulnerability literature [18] and by exposure-sensitivity-adaptive capacity vulnerability assessments applied to composite urban-vulnerability indices [19]; and translates it into a shading-specific KPI architecture, which, to our knowledge, had not been done previously; it examines that structure against a systematically assembled body of 46 case studies and 243 Case × KPI × Comparison rows, rather than illustrative or single-context examples.

Applied to this evidence base, the framework shows that most KPIs are stable in formal definition but not in interpretation: 230 of the 243 comparison rows required climate-dependent interpretation, confirming that a shared unit of measurement does not guarantee cross-climate comparability. This operational distinction between climate-invariant definitions and climate-sensitive assessments—not previously formalised within a shading-specific indicator structure—constitutes the principal methodological contribution of the study and directly addresses the central research question motivating this work. The recurring associations identified between physical mechanism, application scale, and climatic context further show that the proposed classification holds consistently across a heterogeneous evidence base, answering the fourth research question, rather than describing an idealised taxonomy without empirical application. The evidence base is unevenly distributed across climate families, with temperate and arid contexts accounting for most of the analysed cases, while continental and tropical contexts remain sparsely represented. This imbalance limits the extent to which the transferability of KPI interpretation and calibration requirements can be assessed across less represented climates and points to an evidence gap in the current literature. Further studies in these contexts would therefore be valuable for testing the applicability of the proposed framework across a broader range of climatic conditions.

The framework has implications for three user communities. For researchers, it provides a shared structure to improve comparability across studies conducted in different climates and at different spatial scales. For designers and planners, it supports early-stage decision-making by linking shading typologies to relevant KPIs before detailed simulation

or monitoring is undertaken. For policy and benchmarking, it clarifies which indicators may support general guidance and which require local calibration before being incorporated into municipal guidelines or urban heat-mitigation plans. At the same time, the framework should not be interpreted as a predictive or ranking tool: it does not assign universal performance values to shading typologies. Its contribution is methodological, providing a structured basis for selecting, interpreting, and calibrating KPIs in future empirical, simulation-based, or comparative studies.

Limitations

Several limitations should be considered when interpreting the findings of this study. First, the systematic search was conducted using Scopus as the sole bibliographic database and was restricted to publications in English; relevant evidence indexed elsewhere or published in other languages may therefore not have been captured. Second, the OASIS evidence base is unevenly distributed across climatic contexts, with most case studies located in temperate and arid climates and limited representation of continental and tropical conditions. Morphological self-shading is also represented by only one case study, limiting the generalisability of conclusions for this category.

Third, the reviewed evidence is heterogeneous in terms of measurement methods, simulation approaches, baseline conditions, temporal resolution, spatial scale, and reporting of uncertainty and model validation. Although the quantitative synthesis was restricted to physically and temporally comparable observations and conducted at the case level, these differences limit direct quantitative comparability across studies. The climate-group summaries should therefore be interpreted as descriptive patterns within the available evidence rather than as pooled or causal estimates.

Finally, differences between climate groups cannot be attributed to climate alone, as the distribution of shading mechanisms, application scales, measured quantities, methodological approaches, and baseline conditions also varies across the evidence base. The framework should therefore be understood as an evidence-structuring and interpretation tool rather than as a basis for establishing causal climate effects or universal performance rankings.

9. Conclusions

This evidence-based synthesis developed a multiscale, cross-climate KPI framework for assessing the contribution of shading systems to overheating resilience, which was applied to 46 published case studies and 243 Case $\times$ KPI $\times$ Comparison rows.

The main conclusions are structured below according to the four research questions guiding the study.

RQ1. Overheating resilience in shading systems is best understood through complementary dimensions of exposure, thermal sensitivity, and adaptive capacity at the shading-system level. These dimensions distinguish solar and climatic exposure from thermal response and the capacity of shading systems to adjust to changing conditions. The framework uses the IPCC resilience concepts as a conceptual reference while operationalising them specifically for shading systems.

RQ2. Shading systems can be classified through a common structure combining application scale, physical mechanism, temporal behaviour, and resilience contribution. KPIs can likewise be harmonised across building and urban applications, provided that differences in scale, receptor, baseline, temporal resolution, and climatic context are retained. Their formal definitions may remain stable, but their interpretation is not necessarily climate-independent.

RQ3. The proposed framework integrates shading typology, scale, resilience dimension, KPI family, and climate dependency into a common analytical structure. Across

the 243 comparison rows, 230 required climate-dependent interpretation, showing that shared units or calculation procedures do not guarantee direct cross-climate comparability. The framework therefore supports structured interpretation rather than universal ranking or prediction.

RQ4. The evidence base is unevenly distributed across climates, scales, typologies, and KPI families, with temperate and arid contexts more represented than continental and tropical ones. Thermal and overheating indicators dominate the database, while visual, energy, exposure, and adaptive-capacity indicators are less consistently represented. The framework provides a structured way to interpret this heterogeneous evidence and to identify areas where empirical coverage remains limited.

Overall, the study provides a multiscale and climate-aware framework for selecting, interpreting, and calibrating shading-system KPIs. Its purpose is not to establish universal performance rankings, but to support transparent comparison while preserving the climatic, spatial, temporal, and methodological conditions under which shading performance is assessed.

Author Contributions: Conceptualisation, F.S. and S.A.; methodology, F.S. and S.A.; formal analysis, F.S.; investigation, F.S.; data curation, F.S.; writing—original draft preparation, F.S.; writing—review and editing, F.S. and S.A.; visualisation, F.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The dataset generated and analysed during this study, *OASIS: Overheating and Shading Indicators Dataset for Built Environment Resilience*—comprising the structured database of 46 case studies on shading systems for overheating resilience, coded according to the extraction scheme described in Section Data Extraction and Coding Scheme—is available in the Harvard Dataverse repository at: <https://doi.org/10.7910/DVN/PDCXQH>, accessed on 3 September 2026.

Acknowledgments: This study was developed as part of the authors' activities in the International Energy Agency (IEA) Energy in Buildings and Communities (EBC) Programme, Annex 97, "Sustainable Cooling in Cities." The cross-scale assessment of shading, overheating resilience, and climate-sensitive performance indicators directly contributes to the Annex's work on sustainable urban cooling. During the preparation of this manuscript, the author used Claude, version Sonnet 5, for the purposes of language editing and improving readability. The author has reviewed and edited the output and takes full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Wamsler, C.; Brink, E.; Rivera, C. Planning for climate change in urban areas: From theory to practice. *J. Clean. Prod.* **2013**, *50*, 68–81. [CrossRef]
2. Sanchez-Rodriguez, R. Learning to adapt to climate change in urban areas. A review of recent contributions. *Curr. Opin. Environ. Sustain.* **2009**, *1*, 201–206. [CrossRef]
3. Zeleňáková, M.; Purcz, P.; Hlavatá, H.; Blišťan, P. Climate Change in Urban Versus Rural Areas. *Procedia Eng.* **2015**, *119*, 1171–1180. [CrossRef]
4. Chen, K.; Newman, A.J.; Huang, M.; Coon, C.; Darrow, L.A.; Strickland, M.J.; Holmes, H.A. Estimating Heat-Related Exposures and Urban Heat Island Impacts: A Case Study for the 2012 Chicago Heatwave. *GeoHealth* **2022**, *6*, e2021GH000535. [CrossRef] [PubMed]
5. Cuce, P.M.; Cuce, E.; Santamouris, M. Towards Sustainable and Climate-Resilient Cities: Mitigating Urban Heat Islands Through Green Infrastructure. *Sustainability* **2025**, *17*, 1303. [CrossRef]

6. Abedrabboh, O.; Fountoukis, C.; Al-Ansari, T.; Alfarrar, M.R. Enhancing outdoor thermal comfort in a historical marketplace of a hot arid climate through integrated heat mitigation strategies. *City Environ. Interact.* **2026**, *30*, 100393. [CrossRef]
7. Eisenstein, M. How cities can keep their cool. *Nature* **2025**, *648*, S2–S4. [CrossRef] [PubMed]
8. Unger, J.; Skarbit, N.; Kovács, A.; Gál, T. Comparison of regional and urban outdoor thermal stress conditions in heatwave and normal summer periods: A case study. *Urban Clim.* **2020**, *32*, 100619. [CrossRef]
9. Tavares, S.G.; Abuseif, M.; Dupré, K. Urban Heat Mitigation in a Tropical Climate: A Computer Simulation-Based Study in Townsville, Australia. *City Environ. Interact.* **2025**, *27*, 100211. [CrossRef]
10. Tasan, M.; Dąbrowska, J.; Michałowska, K. Surface urban heat islands during heatwaves: Thermal impacts on the built environment in selected polish cities. *Build. Environ.* **2025**, *285*, 113603. [CrossRef]
11. Chen, C.; Hou, H.; Shi, Y.; Zhao, P.; Li, Y.; Wang, Y.; Zhang, Y.; Hu, T. Impact of Different Building Roof Types on Hydrological Processes at the Urban Community Scale. *Hydrology* **2025**, *12*, 154. [CrossRef]
12. [Heat Wave 2026] Cooling Ladder 2.0: It's Time to Cool Cities Before Buildings. Shady Attia. Available online: <https://www.shady-attia.org/heat-wave-2026-cooling-ladder-2-0-its-time-to-cool-cities-before-buildings/> (accessed on 29 August 2026).
13. Meerow, S.; Newell, J.P.; Stults, M. Defining urban resilience: A review. *Landsc. Urban Plan.* **2016**, *147*, 38–49. [CrossRef]
14. Diana, L.; Sommese, F.; Ausiello, G.; Polverino, F. New Green Spaces for Urban Areas: A Resilient Opportunity for Urban Health. In *Resilience vs Pandemics: Innovations in Public Places and Buildings*; Cheshmehzangi, A., Sedrez, M., Zhao, H., Li, T., Heath, T., Dawodu, A., Eds.; Springer Nature: Singapore, 2024; pp. 37–53. [CrossRef]
15. Elrefai, R.; Nikolopoulou, M. A simplified outdoor shading assessment method (OSAM) to identify outdoor shading requirements over the year within an urban context. *Sustain. Cities Soc.* **2023**, *97*, 104773. [CrossRef]
16. Hraska, J. Adaptive solar shading of buildings. *Int. Rev. Appl. Sci. Eng.* **2018**, *9*, 107–113. [CrossRef]
17. Camporeale, P.E.; Mercader-Moyano, P. Retrofit strategies to mitigate overheating linking urban climate modeling and urban building simulations with outdoor comfort. An urban sector in Malaga (Spain). *Energy Build.* **2023**, *298*, 113531. [CrossRef]
18. IPCC. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2007.
19. Zhang, R.; Jiang, A.; Jiang, L. Exposure-Sensitivity-Adaptability (ESA) framework based evaluation and characteristics analysis of urban disasters vulnerability in China. *Ecol. Indic.* **2025**, *176*, 113662. [CrossRef]
20. Sommese, F.; Attia, S. *OASIS: Overheating and Shading Indicators Dataset for Built Environment Resilience*; Harvard Dataverse: Cambridge, MA, USA, 2026. [CrossRef]
21. Amirzadeh, M.; Sobhaninia, S.; Sharifi, A. Urban resilience: A vague or an evolutionary concept? *Sustain. Cities Soc.* **2022**, *81*, 103853. [CrossRef]
22. Fouda, Y.E.; ElKhazendar, D.M. Achievement of resilience in urbanism: A prototype for a simulative methodology. *Alex. Eng. J.* **2023**, *70*, 145–168. [CrossRef]
23. Klein, R.J.T.; Nicholls, R.J.; Thomalla, F. Resilience to natural hazards: How useful is this concept? *Glob. Environ. Change Part B Environ. Hazards* **2003**, *5*, 35–45. [CrossRef]
24. Holling, C.S. Resilience and Stability of Ecological Systems. *Annu. Rev. Ecol. Syst.* **1973**, *4*, 1–23. [CrossRef]
25. National Academies of Sciences, Engineering, and Medicine. *Engineering Within Ecological Constraints*; National Academies Press: Washington, DC, USA, 1996.
26. Meerow, S.; Newell, J.P. Urban resilience for whom, what, when, where, and why? *Urban Geogr.* **2019**, *40*, 309–329. [CrossRef]
27. Folke, C. Resilience: The emergence of a perspective for social–ecological systems analyses. *Glob. Environ. Change* **2006**, *16*, 253–267. [CrossRef]
28. Bautista-Puig, N.; Benayas, J.; Mañana-Rodríguez, J.; Suárez, M.; Sanz-Casado, E. The role of urban resilience in research and its contribution to sustainability. *Cities* **2022**, *126*, 103715. [CrossRef]
29. Zeng, X.; Yu, Y.; Yang, S.; Lv, Y.; Sarker, M.N.I. Urban Resilience for Urban Sustainability: Concepts, Dimensions, and Perspectives. *Sustainability* **2022**, *14*, 2481. [CrossRef]
30. Zhang, C.; Kazanci, O.B.; Levinson, R.; Heiselberg, P.; Olesen, B.W.; Chiesa, G.; Sodagar, B.; Ai, Z.; Selkowitz, S.; Zinzi, M.; et al. Resilient cooling strategies—A critical review and qualitative assessment. *Energy Build.* **2021**, *251*, 111312. [CrossRef]
31. Yao, J.; Chen, G.; Yao, B.; Wu, J. Urban resilience assessment matrix considering spatiotemporal processes: Model proposal and application. *Sustain. Cities Soc.* **2025**, *135*, 106988. [CrossRef]
32. Masnavi, M.R.; Gharai, F.; Hajibandeh, M. Exploring urban resilience thinking for its application in urban planning: A review of literature. *Int. J. Environ. Sci. Technol.* **2019**, *16*, 567–582. [CrossRef]
33. Datola, G. Implementing urban resilience in urban planning: A comprehensive framework for urban resilience evaluation. *Sustain. Cities Soc.* **2023**, *98*, 104821. [CrossRef]
34. Broere, W.; Mitew-Czajewska, M. Urban underground space for resilient cities. *Tunn. Undergr. Space Technol.* **2026**, *170*, 107412. [CrossRef]

35. Liang, C.; Guan, M. Increasing flood hazards threaten metro system resilience under climate and demographic changes. *Sustain. Cities Soc.* **2025**, *133*, 106890. [CrossRef]
36. Yuan, Y.; Zheng, Y.; Zhai, J.; Huang, X.; Yao, M.; Shi, J. How does the sponge city pilot policy affect the urban water system climate resilience: Quasi-experimental evidence from China. *Urban Clim.* **2025**, *64*, 102643. [CrossRef]
37. Sommese, F. *Re-Thinking the Building Envelope: Lessons from Nature in the Era of Climate Change*; Synthesis Lectures on Engineering, Science, and Technology; Springer: Cham, Switzerland, 2024. [CrossRef]
38. Al-Masrani, S.M.; Al-Obaidi, K.M. Dynamic shading systems: A review of design parameters, platforms and evaluation strategies. *Autom. Constr.* **2019**, *102*, 195–216. [CrossRef]
39. Al Dakheel, J.; Tabet Aoul, K. Building Applications, Opportunities and Challenges of Active Shading Systems: A State-of-the-Art Review. *Energies* **2017**, *10*, 1672. [CrossRef]
40. Brzezicki, M. A Systematic Review of the Most Recent Concepts in Kinetic Shading Systems with a Focus on Biomimetics: A Motion/Deformation Analysis. *Sustainability* **2024**, *16*, 5697. [CrossRef]
41. Naik, N.S.; Elzeyadi, I.; Cartwright, V. Dynamic solar screens for high-performance buildings—A critical review of perforated external shading systems. *Archit. Sci. Rev.* **2022**, *65*, 217–231. [CrossRef]
42. Attia, S.; Bilir, S.; Safy, T.; Struck, C.; Loonen, R.; Goia, F. Current trends and future challenges in the performance assessment of adaptive façade systems. *Energy Build.* **2018**, *179*, 165–182. [CrossRef]
43. Loonen, R.C.G.M.; Trčka, M.; Cóstola, D.; Hensen, J.L.M. Climate adaptive building shells: State-of-the-art and future challenges. *Renew. Sustain. Energy Rev.* **2013**, *25*, 483–493. [CrossRef]
44. Carlucci, F.; Loonen, R.C.G.M.; Fiorito, F.; Hensen, J.L.M. A novel approach to account for shape-morphing and kinetic shading systems in building energy performance simulations. *J. Build. Perform. Simul.* **2023**, *16*, 346–365. [CrossRef]
45. Sommese, F.; Badarnah, L.; Ausiello, G. A critical review of biomimetic building envelopes: Towards a bio-adaptive model from nature to architecture. *Renew. Sustain. Energy Rev.* **2022**, *169*, 112850. [CrossRef]
46. Sommese, F.; Badarnah, L.; Ausiello, G. Smart materials for biomimetic building envelopes: Current trends and potential applications. *Renew. Sustain. Energy Rev.* **2023**, *188*, 113847. [CrossRef]
47. Sommese, F.; Ausiello, G. From Nature to Architecture for Low Tech Solutions: Biomimetic Principles for Climate-Adaptive Building Envelope. In *Technological Imagination in the Green and Digital Transition*; Arbizzani, E., Cangelli, E., Clemente, C., Cumo, F., Giofrè, F., Giovenale, A.M., Palme, M., Paris, S., Eds.; Springer International Publishing: Cham, Switzerland, 2023; pp. 429–438. [CrossRef]
48. Badarnah, L. Form Follows Environment: Biomimetic Approaches to Building Envelope Design for Environmental Adaptation. *Buildings* **2017**, *7*, 40. [CrossRef]
49. Al-Obaidi, K.M.; Ismail, M.A.; Hussein, H.; Rahman, A.M.A. Biomimetic building skins: An adaptive approach. *Renew. Sustain. Energy Rev.* **2017**, *79*, 1472–1491. [CrossRef]
50. Sommese, F.; Ausiello, G. A biomimetic approach for climate reactive building envelopes inspired by plants adaptive strategies. In *In Transition: Challenges and Opportunities for the Build Heritage*; EdicomEdizioni: Monfalcone, Italy, 2023.
51. Şık, C.I.S.; Woźniczka, A.; Widera, B. A Conceptual Framework for the Design of Energy-Efficient Vertical Green Façades. *Energies* **2022**, *15*, 8069. [CrossRef]
52. Hunter, A.M.; Williams, N.S.G.; Rayner, J.P.; Aye, L.; Hes, D.; Livesley, S.J. Quantifying the thermal performance of green façades: A critical review. *Ecol. Eng.* **2014**, *63*, 102–113. [CrossRef]
53. Convertino, F.; Vox, G.; Schettini, E. Evaluation of the cooling effect provided by a green façade as nature-based system for buildings. *Build. Environ.* **2021**, *203*, 108099. [CrossRef]
54. Chàfer, M.; Pisello, A.L.; Piselli, C.; Cabeza, L.F. Greenery System for Cooling Down Outdoor Spaces: Results of an Experimental Study. *Sustainability* **2020**, *12*, 5888. [CrossRef]
55. Amores, T.R.P.; Ramos, J.S.; Delgado, M.G.; Medina, D.C.; Cerezo-Narvaéz, A.; Domínguez, S.Á. Effect of green infrastructures supported by adaptative solar shading systems on livability in open spaces. *Urban For. Urban Green.* **2023**, *82*, 127886. [CrossRef]
56. Sommese, F. Nature-Based Solutions to Enhance Urban Resilience in the Climate Change and Post-Pandemic Era: A Taxonomy for the Built Environment. *Buildings* **2024**, *14*, 2190. [CrossRef]
57. Nature-Based Solutions|IUCN. Available online: <https://iucn.org/our-work/nature-based-solutions> (accessed on 18 February 2025).
58. Cohen-Shacham, E.; Walters, G.; Janzen, C.; Maginnis, S. (Eds.) *Nature-Based Solutions to Address Global Societal Challenges*; IUCN International Union for Conservation of Nature: Gland, Switzerland, 2016. [CrossRef]
59. Battista, G.; de Lieto Vollaro, E.; Ochoń, P.; de Lieto Vollaro, R. Effects of urban heat island mitigation strategies in an urban square: A numerical modelling and experimental investigation. *Energy Build.* **2023**, *282*, 112809, Erratum in *Energy Build.* **2023**, *300*, 113475. [CrossRef]

60. Sommesse, F. Nature-Based Solutions as Climate Change Adaptation Measures: Lessons and Best-Practices from European Cities. In *Proceedings of the 11th International Conference of Ar.Tec. (Scientific Society of Architectural Engineering)*; Corrao, R., Campisi, T., Colajanni, S., Saeli, M., Vinci, C., Eds.; Springer Nature: Cham, Switzerland, 2025; pp. 678–691. [\[CrossRef\]](#)
61. Sommesse, F.; Diana, L.; Colajanni, S.; Bellomo, M.; Sciuto, G.; Lombardo, G. Towards a Regenerative and Climate-Resilient Built Environment: Greening Lessons from European Cities. *Buildings* **2025**, *15*, 1878. [\[CrossRef\]](#)
62. Rocca, M.; Salvadori, G.; Leccese, F.; Bisegna, F. Textile solar shading systems for reducing the negative impacts of solar radiation in urban areas: A critical review. *City Environ. Interact.* **2025**, *28*, 100240. [\[CrossRef\]](#)
63. Rinchumphu, D.; Suriyanon, N.; Phichetkunbodee, N.; Munlikawong, S.; Wanitchayapaisit, C.; Sitthikankun, S. Economics and cost effectiveness of a rain garden for flood-resistant urban design. *Glob. J. Environ. Sci. Manag.* **2024**, *10*, 1–12. [\[CrossRef\]](#)
64. Zhang, Z.; Zhang, Y.; Li, J.; Sun, Y.; Liu, Z. Pollutant accumulation and microbial community evolution in rain gardens with different drainage types at field scale. *Sci. Rep.* **2024**, *14*, 2. [\[CrossRef\]](#) [\[PubMed\]](#)
65. Sierra, P.; Hernández, J.A. Solar heat gain coefficient of water flow glazings. *Energy Build.* **2017**, *139*, 133–145. [\[CrossRef\]](#)
66. Chen, F.; Wittkopf, S.K.; Ng, P.K.; Du, H. Solar heat gain coefficient measurement of semi-transparent photovoltaic modules with indoor calorimetric hot box and solar simulator. *Energy Build.* **2012**, *53*, 74–84. [\[CrossRef\]](#)
67. Moghaddam, S.A.; Simões, N.; da Silva, M.G. Review of the experimental methods for evaluation of windows' solar heat gain coefficient: From standardized tests to new possibilities. *Build. Environ.* **2023**, *242*, 110527. [\[CrossRef\]](#)
68. Cascone, Y.; Corrado, V.; Serra, V. Calculation procedure of the shading factor under complex boundary conditions. *Sol. Energy* **2011**, *85*, 2524–2539. [\[CrossRef\]](#)
69. Silva, M.; Roberts, J.J.; Prado, P.O. Calculation of the Shading Factors for Solar Modules with MATLAB. *Energies* **2021**, *14*, 4713. [\[CrossRef\]](#)
70. Gueymard, C.A. Direct solar transmittance and irradiance predictions with broadband models. Part I: Detailed theoretical performance assessment. *Sol. Energy* **2003**, *74*, 355–379, Erratum in *Sol. Energy* **2004**, *76*, 513. [\[CrossRef\]](#)
71. King, R.; Buckius, R.O. Direct solar transmittance for a clear sky. *Sol. Energy* **1979**, *22*, 297–301. [\[CrossRef\]](#)
72. ASHRAE Standard 90.1-2022; Energy Standard for Sites and Buildings Except Low-Rise Residential Buildings. ASHRAE: Peachtree Corners, GA, USA, 2023. Available online: <https://www.ashrae.org/technical-resources/bookstore/standard-90-1> (accessed on 18 February 2025).
73. Svensson, M.K. Sky view factor analysis—Implications for urban air temperature differences. *Meteorol. Appl.* **2004**, *11*, 201–211. [\[CrossRef\]](#)
74. Zakšek, K.; Oštir, K.; Kokalj, Ž. Sky-View Factor as a Relief Visualization Technique. *Remote Sens.* **2011**, *3*, 398–415. [\[CrossRef\]](#)
75. Yin, Y.; Li, S.; Xing, X.; Zhou, X.; Kang, Y.; Hu, Q.; Li, Y. Cooling Benefits of Urban Tree Canopy: A Systematic Review. *Sustainability* **2024**, *16*, 4955. [\[CrossRef\]](#)
76. Ruiz-Valero, Á.; Pereña-Ortiz, J.F.; Martín-Lozano, I.; Cortés-Molino, Á.; Cozano-Pérez, P.; Galindo-Ruiz, B.; Díaz-Galiano, L.A.; Salvo-Tierra, Á.E. Quantifying urban tree canopy cooling capacity using Bayesian hierarchical models and satellite imagery. *Plants People Planet* **2026**, *8*, 338–352. [\[CrossRef\]](#)
77. Barrell, J. Tree canopy cover assessment for urban planning; towards an international model for improving climate adaptation and nature recovery decisions. *Arboric. J.* **2026**, *48*, 4–20. [\[CrossRef\]](#)
78. Yan, G.; Hu, R.; Luo, J.; Weiss, M.; Jiang, H.; Mu, X.; Xie, D.; Zhang, W. Review of indirect optical measurements of leaf area index: Recent advances, challenges, and perspectives. *Agric. For. Meteorol.* **2019**, *265*, 390–411. [\[CrossRef\]](#)
79. Lai, Y.; Mu, X.; Fan, D.; Zou, J.; Chen, J.M.; Li, W.; Xie, D.; Yan, G. Imaging orientation matters: Challenges in leaf area index measurement on slopes via levelled versus tilted photography. *Agric. For. Meteorol.* **2026**, *380*, 111083. [\[CrossRef\]](#)
80. Schünemann, C.; Schiela, D.; Ortlepp, R. Guidelines to Calibrate a Multi-Residential Building Simulation Model Addressing Overheating Evaluation and Residents' Influence. *Buildings* **2021**, *11*, 242. [\[CrossRef\]](#)
81. EN 16798-1:2019; Energy Performance of Buildings—Ventilation for Buildings—Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics. International Organization for Standardization: Geneva, Switzerland, 2019. Available online: <https://standards.iteh.ai/catalog/standards/cen/b4f68755-2204-4796-854a-56643dfcf89/en-16798-1-2019> (accessed on 18 February 2025).
82. Barbero-Barrera, M.d.M.; Tintero-Caballero, R.; de Viedma-Santoro, M.G. Impact of Solar Shading on Façades' Surface Temperatures under Summer and Winter Conditions by IR Thermography. *Architecture* **2024**, *4*, 221–246. [\[CrossRef\]](#)
83. Siewczyńska, M.; Ksib, B. Effectiveness of Screens Shading Opaque Facades in Terms of Building Thermal Modernisation. *Civ. Environ. Eng. Rep.* **2024**, *34*, 126–137. [\[CrossRef\]](#)
84. EN ISO 7730:2005; Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria. International Organization for Standardization: Geneva, Switzerland, 2005.
85. Evangelisti, L.; Guattari, C.; Asdrubali, F.; de Lieto Vollaro, R. An experimental investigation of the thermal performance of a building solar shading device. *J. Build. Eng.* **2020**, *28*, 101089. [\[CrossRef\]](#)

86. ISO 52016-1:2017; Energy Performance of Buildings—Energy Needs for Heating and Cooling, Internal Temperatures and Sensible and Latent Heat Loads Part 1: Calculation Procedures. ISO: Geneva, Switzerland, 2017.
87. Evren, F.; Biswas, S.; Graves, R. Measuring mean radiant temperature for indoor comfort assessment using low-resolution optical sensors. *Nat. Commun.* **2025**, *16*, 1215. [[CrossRef](#)] [[PubMed](#)]
88. van der Veld, M.; Steeneveld, G.-J.; Savić, S.; Dunjić, J.; Arsenović, D.; Milošević, D. Directional Mean Radiant Temperature Decomposition Reveals Micro-Scale Drivers of Urban Heat Stress in Novi Sad (Serbia). *Sustain. Cities Soc.* **2026**, *149*, 107717. [[CrossRef](#)]
89. Michelini, B.A. Effect of Urban Trees in Eberswalde on Mean Radiant Temperature and Shadow Patterns—A Case Study. In *Umweltinformationssysteme—Digitale Innovationen für Eine Nachhaltige Zukunft*; Fuchs-Kittowski, F., Abecker, A., Hosenfeld, F., Reineke, A., Wachsmuth, M., Eds.; Springer Fachmedien: Wiesbaden, Germany, 2026; pp. 159–181. [[CrossRef](#)]
90. Lee, D.-S.; Jo, J.-H. Measuring and implementing mean radiant temperature in buildings: Technical review. *Renew. Sustain. Energy Rev.* **2025**, *207*, 114908. [[CrossRef](#)]
91. Sun, J. Development of dynamic shading control for daylight measures in green buildings towards overall energy efficiency of lighting and air-conditioning systems. *Low Carbon Mater. Green Constr.* **2023**, *1*, 22. [[CrossRef](#)]
92. Sommese, F.; Diana, L. A holistic framework for the implementation of green roofs on existing buildings: A case study in the Mediterranean climate of Naples. *Build. Environ.* **2025**, *274*, 112811. [[CrossRef](#)]
93. Thapa, S.; Rijal, H.B.; Zaki, S.A. District-wise evaluation of meteorological factors and outdoor thermal comfort in India using UTCI—Insight into future climatic scenario. *Sustain. Cities Soc.* **2024**, *116*, 105840. [[CrossRef](#)]
94. Nie, T.; Lai, D.; Liu, K.; Lian, Z.; Yuan, Y.; Sun, L. Discussion on inapplicability of Universal Thermal Climate Index (UTCI) for outdoor thermal comfort in cold region. *Urban Clim.* **2022**, *46*, 101304. [[CrossRef](#)]
95. Mahdavejad, M.; Shaeri, J.; Nezami, A.; Goharian, A. Comparing universal thermal climate index (UTCI) with selected thermal indices to evaluate outdoor thermal comfort in traditional courtyards with BWh climate. *Urban Clim.* **2024**, *54*, 101839. [[CrossRef](#)]
96. Li, J.; Rao, J.; Wang, L. The Effect of Street Orientation on the Temporal Variation in Thermal Environment Within Streets in Different Climate Zones. *Buildings* **2025**, *15*, 1506. [[CrossRef](#)]
97. Pierucci, G.; Baia, M.; Balocco, C. Urban Area Sustainability Analysis by Means of Integrated Microclimatic Measurement Techniques Combined with Thermal Comfort Modelling—A Pilot Project Application. *Energies* **2026**, *19*, 217. [[CrossRef](#)]
98. Premier, A. Solar shading devices integrating smart materials: An overview of projects, prototypes and products for advanced façade design. *Archit. Sci. Rev.* **2019**, *62*, 455–465. [[CrossRef](#)]
99. Rotas, R.; Fotopoulou, M.; Drosatos, P.; Rakopoulos, D.; Nikolopoulos, N. Adaptive Dynamic Building Envelopes with Solar Power Components: Annual Performance Assessment for Two Pilot Sites. *Energies* **2023**, *16*, 2148. [[CrossRef](#)]
100. Golzan, S.S.; Pouyanmehr, M.; Naeini, H.S. Recommended angle of a modular dynamic façade in hot-arid climate: Daylighting and energy simulation. *Smart Sustain. Built Environ.* **2021**, *12*, 27–37. [[CrossRef](#)]
101. Wujeska-Klaue, A.; Pfautsch, S. The Best Urban Trees for Daytime Cooling Leave Nights Slightly Warmer. *Forests* **2020**, *11*, 945. [[CrossRef](#)]
102. Paschalis, A.; Chakraborty, T.; Fatichi, S.; Meili, N.; Manoli, G. Urban Forests as Main Regulator of the Evaporative Cooling Effect in Cities. *AGU Adv.* **2021**, *2*, e2020AV000303. [[CrossRef](#)]
103. Elnabawi, M.H.; Hamza, N. A Behavioural Analysis of Outdoor Thermal Comfort: A Comparative Analysis between Formal and Informal Shading Practices in Urban Sites. *Sustainability* **2020**, *12*, 9032. [[CrossRef](#)]
104. Esfehankalateh, A.T.; Ngarambe, J.; Yun, G.Y. Influence of Tree Canopy Coverage and Leaf Area Density on Urban Heat Island Mitigation. *Sustainability* **2021**, *13*, 7496. [[CrossRef](#)]
105. Mangkuto, R.A.; Koerniawan, M.D.; Apriliyanthi, S.R.; Lubis, I.H.; Atthailah; Hensen, J.L.; Paramita, B. Design Optimisation of Fixed and Adaptive Shading Devices on Four Façade Orientations of a High-Rise Office Building in the Tropics. *Buildings* **2022**, *12*, 25. [[CrossRef](#)]
106. Naboni, E.; Marchesini, G.E.; Grifoni, R.C. 3D façade geometry as a dual passive control in hot urban canyons: Reducing street MRT and cooling loads. *Build. Environ.* **2026**, *297*, 114479. [[CrossRef](#)]
107. Poiss, M.; Briefer, A.; Scharf, B.; Spörl, P.; Stangl, R. Vertical greenery as natural shading of glass facades: Bioshading coefficients for 4 climbing plant species for assessment of shading performance. *Build. Environ.* **2025**, *283*, 113399. [[CrossRef](#)]
108. Koç, S.G.; Kalfa, S.M. The effects of shading devices on office building energy performance in Mediterranean climate regions. *J. Build. Eng.* **2021**, *44*, 102653. [[CrossRef](#)]
109. Salonen, T.; Hollands, J.; Sesto, E.; Korjenic, A. Thermal Effects of Vertical Greening in Summer: An Investigation on Evapotranspiration and Shading of Façade Greening in Vienna. *Buildings* **2022**, *12*, 1705. [[CrossRef](#)]
110. Ouyang, W.; Ren, G.; Tan, Z.; Li, Y.; Ren, C. Natural shading vs. artificial shading: A comparative analysis of their cooling efficacy in extreme hot weather. *Urban Clim.* **2024**, *55*, 101870. [[CrossRef](#)]

111. Speak, A.; Montagnani, L.; Wellstein, C.; Zerbe, S. The influence of tree traits on urban ground surface shade cooling. *Landsc. Urban Plan.* **2020**, *197*, 103748. [[CrossRef](#)]
112. Oraipoulos, A.; Wieser, M.; Verdieri, M.; Lambert, R.; Fennell, P.; Ruyssevelt, P. Improving habitability in informal settlements in the Global South: Exploring the impact of community urban green infrastructure on outdoor heat stress. *Build. Environ.* **2026**, *287*, 113787. [[CrossRef](#)]
113. Gillerot, L.; Landuyt, D.; De Frenne, P.; Muys, B.; Verheyen, K. Urban tree canopies drive human heat stress mitigation. *Urban For. Urban Green.* **2024**, *92*, 128192. [[CrossRef](#)]
114. Nasrollahi, N.; Namazi, Y.; Taleghani, M. The effect of urban shading and canyon geometry on outdoor thermal comfort in hot climates: A case study of Ahvaz, Iran. *Sustain. Cities Soc.* **2021**, *65*, 102638. [[CrossRef](#)]
115. Mahmoud, R.M.A.; Abdallah, A.S.H. Assessment of outdoor shading strategies to improve outdoor thermal comfort in school courtyards in hot and arid climates. *Sustain. Cities Soc.* **2022**, *86*, 104147. [[CrossRef](#)]
116. Abaas, Z.R.; Khalid, Z. Towards local sustainability: A case study to evaluate outdoor urban spaces in Baghdad using physiological equivalent temperature index. *City Environ. Interact.* **2023**, *20*, 100115. [[CrossRef](#)]
117. Al Tahir, I.; El Fattah, A.A.; Mohammed, M.; Asif, M.; Almahdy, O. Evaluating the performance of outdoor shading devices on human thermal comfort in hot humid climates: A case study of Dhahran. *Build. Environ.* **2025**, *271*, 112625. [[CrossRef](#)]
118. Yin, S.; Wang, F.; Xiao, Y.; Xue, S. Comparing cooling efficiency of shading strategies for pedestrian thermal comfort in street canyons of traditional shophouse neighbourhoods in Guangzhou, China. *Urban Clim.* **2022**, *43*, 101165. [[CrossRef](#)]
119. Sommese, F.; Diana, L. Scenario-based simulation of greening adaptation strategies in a dense historic urban fabric: A comparative analysis for the case of Naples, Italy. *Sustain. Cities Soc.* **2026**, *145*, 107488. [[CrossRef](#)]
120. Rahman, M.A.; Dervishi, V.; Moser-Reischl, A.; Ludwig, F.; Pretzsch, H.; Rötzer, T.; Pauleit, S. Comparative analysis of shade and underlying surfaces on cooling effect. *Urban For. Urban Green.* **2021**, *63*, 127223. [[CrossRef](#)]
121. Dehghan Lotfabad, A.; Hosseini, S.M.; Dabove, P.; Heiranipour, M.; Sommese, F. Impacts of Vertical Greenery on Outdoor Thermal Comfort and Carbon Emission Reduction at the Urban Scale in Turin, Italy. *Buildings* **2025**, *15*, 450. [[CrossRef](#)]
122. Lam, C.K.C.; Weng, J.; Liu, K.; Hang, J. The effects of shading devices on outdoor thermal and visual comfort in Southern China during summer. *Build. Environ.* **2023**, *228*, 109743. [[CrossRef](#)]
123. Hoelscher, M.-T.; Nehls, T.; Jänicke, B.; Wessolek, G. Quantifying cooling effects of facade greening: Shading, transpiration and insulation. *Energy Build.* **2016**, *114*, 283–290. [[CrossRef](#)]
124. Sabrin, S.; Karimi, M.; Nazari, R.; Pratt, J.; Bryk, J. Effects of Different Urban-Vegetation Morphology on the Canopy-level Thermal Comfort and the Cooling Benefits of Shade Trees: Case-study in Philadelphia. *Sustain. Cities Soc.* **2021**, *66*, 102684. [[CrossRef](#)]
125. Kuru, A.; Oldfield, P.; Bonser, S.; Fiorito, F. A Framework to Achieve Multifunctionality in Biomimetic Adaptive Building Skins. *Buildings* **2020**, *10*, 114. [[CrossRef](#)]
126. Rossi, F.; Cardinali, M.; Gambelli, A.M.; Filipponi, M.; Castellani, B.; Nicolini, A. Outdoor thermal comfort improvements due to innovative solar awning solutions: An experimental campaign. *Energy Build.* **2020**, *225*, 110341. [[CrossRef](#)]
127. Fabbri, K.; Antonini, E.; Marchi, L. Sun-Shading Sails in Courtyards: An Italian Case Study with RayMan. *Sustainability* **2023**, *15*, 13033. [[CrossRef](#)]
128. Guo, F.; Guo, R.; Zhang, H.; Dong, J.; Zhao, J. A canopy shading-based approach to heat exposure risk mitigation in small squares. *Urban Clim.* **2023**, *49*, 101495. [[CrossRef](#)]
129. Wu, Y.-C.; Lu, C.-L.; Lin, T.-P. Evaluating the effectiveness of tree canopy and building shade in urban heat mitigation using solar radiation transmittance. *Urban Clim.* **2025**, *62*, 102522. [[CrossRef](#)]
130. Garcia-Nevado, E.; Beckers, B.; Coch, H. Assessing the cooling effect of urban textile shading devices through time-lapse thermography. *Sustain. Cities Soc.* **2020**, *63*, 102458. [[CrossRef](#)]
131. Freewan, A.A.; Jaradat, N.M.; Amaireh, I.A. Optimizing Shading and Thermal Performances of Vertical Green Wall on Buildings in a Hot Arid Region. *Buildings* **2022**, *12*, 216. [[CrossRef](#)]
132. Kwon, T.K.; Kim, T.H.; Lim, Y.-S. Exploring the Heat Mitigation Effects of Urban Climate Adaptation Facilities. *Sustainability* **2024**, *16*, 9919. [[CrossRef](#)]
133. Irfeey, A.M.M.; Chau, H.-W.; Sumaiya, M.M.F.; Wai, C.Y.; Muttill, N.; Jamei, E. Sustainable Mitigation Strategies for Urban Heat Island Effects in Urban Areas. *Sustainability* **2023**, *15*, 10767. [[CrossRef](#)]
134. Makvandi, M.; Li, W.; Ou, X.; Chai, H.; Khodabakhshi, Z.; Fu, J.; Yuan, P.F.; Horimbere, E.D.L.J. Urban Heat Mitigation towards Climate Change Adaptation: An Eco-Sustainable Design Strategy to Improve Environmental Performance under Rapid Urbanization. *Atmosphere* **2023**, *14*, 638. [[CrossRef](#)]
135. Bellia, L.; Marino, C.; Minichiello, F.; Pedace, A. An Overview on Solar Shading Systems for Buildings. *Energy Procedia* **2014**, *62*, 309–317. [[CrossRef](#)]

136. Salvati, A.; Kolokotroni, M.; Kotopouleas, A.; Watkins, R.; Giridharan, R.; Nikolopoulou, M. Impact of reflective materials on urban canyon albedo, outdoor and indoor microclimates. *Build. Environ.* **2022**, *207*, 108459. [[CrossRef](#)]
137. Rosso, F.; Golasi, I.; Castaldo, V.L.; Piselli, C.; Pisello, A.L.; Salata, F.; Ferrero, M.; Cotana, F.; de Lieto Vollaro, A. On the impact of innovative materials on outdoor thermal comfort of pedestrians in historical urban canyons. *Renew. Energy* **2018**, *118*, 825–839. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.