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Review Article

A Systematic Review of Shading Systems Across Diverse Climates

A Multi-Criteria Framework for Optimizing Energy Performance and User Comfort*

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Abstract

Problem statement: In many warm, humid, and even temperate climates, managing solar radiation has become an increasingly complex challenge. This is largely due to the fact that most existing shading systems are predominantly designed with a singular focus on reducing energy consumption, often overlooking critical dimensions such as visual comfort, architectural integration, and occupant behavior. Consequently, shading strategies that fail to adopt a multi-dimensional approach frequently yield suboptimal performance and encounter limited acceptance in real-world applications.

Research objective: This study addresses the aforementioned gap by conducting a systematic review of 70 selected scholarly works. The aim is twofold: to establish a comprehensive classification of shading systems based on climatic context, technological characteristics, building typology, and user-centric considerations; and to propose an integrated decision-making framework for the optimal selection and design of shading strategies tailored to varied climatic scenarios.

Research method: The research adopts a systematic review methodology, underpinned by qualitative content analysis. High-impact publications from 2004 to 2024 were curated from authoritative academic databases. These studies were critically assessed based on shading typologies, methodological approaches, performance metrics, and climate contexts. A comparative analysis was then employed to synthesize a multi-criteria framework that integrates energy simulations, parametric optimization, user-centered evaluation, and field calibration techniques.

Conclusion: and Conclusion: The findings reveal that successful shading interventions are those that balance thermal load reduction, adequate daylight provision, user satisfaction, and environmental considerations. The proposed framework emphasizes iterative feedback loops across design, implementation, and post-occupancy evaluation phases. This dynamic, climate-responsive model offers a robust tool for advancing sustainable, human-centered architectural practices.

Keywords: *Shading systems, Systematic review, Energy optimization, User comfort, Climate adaptation.*

Introduction

The building sector, often regarded as the physical backbone of modern civilization, plays a pivotal role in driving economic development and enhancing the quality of human life. However, it is simultaneously one of the largest global consumers of energy and emitters of environmental pollutants. Empirical evidence and international statistics underscore this dichotomy, indicating that the built environment alone accounts for approximately 30–40% of total global final energy consumption and over 40% of worldwide CO_2

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emissions (Mousavi et al., 2025; OECD, 2016). This consumption pattern holds true at the national scale as well, with official reports revealing that nearly 40% of the country's total energy production is consumed by the building sector (Farahmandfar et al., 2025). These stark figures highlight the urgent need for a fundamental rethinking of architectural design paradigms, particularly in relation to energy management and environmental impact mitigation. Among the physical determinants of a building's energy performance, the building envelope—and more specifically façades and fenestration—occupies a critical position. Numerous studies affirm that optimizing the thermal and optical behavior of envelope components can yield energy savings exceeding 50% of a building's total consumption (Hoffmann et al., 2016). Within this context, shading systems, as a cornerstone of bioclimatic architectural design, demonstrate significant potential to reduce solar heat gains, enhance thermal and visual comfort, and diminish reliance on mechanical cooling systems (Kitsopoulou et al., 2024; De Luca et al., 2022). Despite their considerable promise, achieving optimal performance from shading systems remains fraught with challenges. Fixed shading devices, while simple in design and operation, inherently lack the adaptability required to respond to the dynamic variations in climate, solar intensity, and solar angle throughout the diurnal and seasonal cycles. This lack of responsiveness can, in certain contexts, obstruct daylight penetration and inadvertently increase dependence on artificial lighting systems (Al-Tamimi & Fadzil, 2011; Nazari et al., 2023). Conversely, dynamic and adaptive shading systems offer greater operational flexibility but demand the integration of advanced technologies such as environmental sensors, artificial intelligence, smart materials, and kinetic structures (Sendi, 2014; De Luca et al., 2022). Beyond technological constraints, climatic variability and contextual heterogeneity present significant barriers to the transferability of shading solutions. Systems optimized for one climatic region may underperform or even disrupt the thermal and lighting balance in another (Bedon et al., 2018; Hoffmann et al., 2016). Furthermore, human-centered considerations—such as access to natural daylight, glare control, visual connectivity with the outdoors, and perceptual comfort—are critical aspects that must be addressed in tandem with purely energy-driven objectives (Sendi, 2014). Recent evidence suggests that well-designed dynamic shading systems can reduce energy consumption in commercial buildings by up to 30% (Ma et al., 2023; Chou et al., 2016). Nonetheless, most of these studies remain narrowly focused on energy efficiency, with limited exploration of associated dimensions such as daylight quality, occupant well-being, operational sustainability, and economic feasibility (Hoffmann et al., 2016). The absence of holistic, interdisciplinary, and multi-criteria assessment frameworks has contributed to conceptual and practical shortcomings within the literature, particularly in addressing the complex realities of design and operation. In light of these limitations, this study undertakes a systematic review of the scholarly discourse on shading systems across diverse climatic contexts. The objective is to synthesize an integrated understanding of the technological, climatic, and performance-related dimensions of shading strategies. Drawing on a systematic analysis of 70 peer-reviewed articles published between 2004 and 2024, this research seeks to establish a robust foundation for future investigations.

The study is guided by two fundamental research questions:

1.What criteria and methodologies can be employed to develop a comprehensive classification of shading systems based on climatic characteristics, building typologies, and functional objectives?

2.How can an integrated framework be devised to facilitate context-sensitive selection and optimal design of shading systems across diverse environmental scenarios?

Literature Review

Shading systems, as strategic components of sustainable architecture, play a critical role in regulating solar radiation, controlling daylight, reducing cooling loads, and enhancing both thermal and visual comfort within buildings (Datta, 2001; Al-Tamimi et al., 2011). Nevertheless, a review of recent scholarship reveals a predominant focus on isolated performance aspects such as glare control or energy reduction while overlooking the complex interplay of climatic, geometric, and human-centric variables (Kim et al., 2015; Dubois, 2001). In hot-arid climates like those in many Iranian cities (e.g., Isfahan), the performance of shading systems in response to solar intensity and orientation has produced inconsistent and sometimes contradictory outcomes (Esfandiari et al., 2024). A significant gap in the literature concerns the absence of robust multi-criteria evaluations that consider visual comfort, daylight sufficiency, and external view quality (Taveres et al., 2019; Alsharif et al., 2023). Unidimensional approaches risk producing shading solutions that, despite improving thermal conditions, may prove inadequate in environments where daylight quality is critical, such as classrooms or office spaces (Dubois, 2001; Esfandiari & Shokri, 2023). Geometric and mechanical attributes of shading devices, such as louver type and depth, demonstrate divergent effects across climatic regions. A system optimized for energy performance in a tropical climate may, for instance, lead to visual discomfort in Mediterranean zones (Lai et al., 2017; Buratti et al., 2022). Therefore, calibrating simulation models with localized environmental data including surface reflectance, glazing properties, and thermal behavior of materials, is indispensable (Esfandiari & Shokri, 2023; AbdelAziz, 2016). In many studies, reliance on global average datasets embedded in simulation platforms such as TRNSYS and EnergyPlus has significantly undermined the contextual validity of results in Iran's climate zones (Aketouane et al., 2018; Motlagh et al., 2024). Despite technological advancements in smart glazing and photovoltaic louvers (Qingsong et al., 2023; Chou et al., 2016), empirical studies investigating their durability, maintenance demands, and functional viability in arid conditions remain limited (Bellia et al., 2014; Edupuganti, 2013). Moreover, the operational reliability of automated intelligent systems in climates with high dust loads and temperature volatility such as Iran requires further validation under real-world conditions (Freewan, 2014; Esfandiari et al., 2024). In sum, the effective design of shading systems necessitates an integrated and adaptive framework that is responsive to climatic realities, human needs, and technological capacities. Such a framework must be grounded in local data, informed by multiple performance criteria including comfort, illumination, and glare control, and subjected to long-term field validation. It must also align with the principles of context-sensitive and climate-responsive architecture within the Iranian built environment (Palmero-Marrero & Oliveira, 2010). To address this, the present study systematically reviews 70 peer-reviewed articles (2004–2024) and critically engages with national scholarship (e.g., Esfandiari et al., 2024) to identify conceptual gaps and establish a theoretical foundation for advancing multi-criteria and climate-adaptive shading design in contemporary Iranian architecture.

Literature Review

Recent investigations into shading systems confirm their essential role in improving energy performance, managing daylight, and enhancing thermal and visual comfort. For example, Kirimtat et al. (2016) conducted a review of literature from 1996 to 2015, classifying shading devices based on climatic parameters and architectural design typologies. Their energy and daylight simulation analyses affirmed the significant role of shading in reducing energy demand while underscoring the importance of climate-specific design strategies. In the domain of automated façade control, Tabadkani et al. (2020) emphasized the inadequacy of multi-objective control frameworks in existing research. They advocated for the integration of dynamic, intelligent systems capable of adapting to fluctuating environmental conditions. However, most prior studies remain fixated on conventional shading solutions such as roller blinds or venetian systems, neglecting the inclusion of user preferences within control algorithms and the development of responsive, real-time systems. Despite these contributions, the literature still lacks a coherent and structured framework for categorizing shading systems in a manner that integrates climatic, functional, and aesthetic dimensions. The present research addresses this gap by systematically identifying and synthesizing the drivers of effective shading system design through a multi-dimensional lens. This integrative approach aims to deliver actionable design strategies for advancing sustainable and performance-oriented architecture.

Research Methodology

This study adopts a systematic review methodology grounded in analytical and evidence-based inquiry. Following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol, a comprehensive search was conducted using targeted keywords related to shading systems, energy efficiency, thermal comfort, visual comfort, and climate adaptability. These terms were applied across multiple reputable academic databases, including Web of Science, Scopus, IEEE Xplore, ScienceDirect, and Google Scholar. To ensure the currency of the review, studies published after 2020 were prioritized. However, foundational or highly cited studies from earlier periods were also included to strengthen the theoretical depth of the analysis. During the screening phase, inclusion criteria encompassed peer-reviewed status, empirical evidence, and direct relevance to energy and comfort-related themes. Two independent experts reviewed the titles, abstracts, and full texts to ensure both methodological rigor and alignment with the research objectives. Ultimately, 70 high-quality articles were selected for in-depth analysis. Structured data extraction was conducted using a standardized protocol, capturing bibliographic metadata, methodological approaches, climatic contexts, key performance indicators, and shading system typologies. To assess article validity, a modified version of the Critical Appraisal Skills Programme (CASP) checklist was employed. Only those articles that scored adequately on methodological quality, contextual applicability, and climatic relevance were retained for final synthesis. Quantitative and qualitative findings were then synthesized thematically across three core dimensions:

1.Climatic Conditions,
2.Building Typologies, and
3.Performance Outcomes (with a focus on energy reduction and thermal–visual comfort enhancement).

The compiled dataset was analyzed using R Studio, allowing for the identification of dominant trends and critical research gaps. The insights derived from this synthesis form the basis for developing an integrative framework to inform the design and selection of shading systems in climate-responsive and sustainable architectural practice. Given the extensive scope of the review, the bibliographic and analytical details of 20 selected studies are presented in Tables 1 & 2. Each row in these tables summarizes a given article based on its full bibliographic reference (title, year of publication), methodological orientation, investigated parameters, and type(s) of shading systems analyzed. Additionally, the tables denote the geographical and climatic zones in which each study was conducted, highlighting the diversity of environmental contexts represented in the review.

Bibliometric Analysis

An examination of the temporal distribution of the 70 selected articles between 2004 and 2024 reveals a distinct evolution in scholarly attention toward solar control and shading systems. In the early phase (2004–2010), the number of studies remained limited, largely due to the nascent state of foundational research in solar radiation control and architectural shading. However, from 2011 onward, coinciding with a global shift toward energy sustainability and the rapid advancement of simulation technologies, the rate of publication accelerated significantly. This trend culminated in a marked peak during the 2020–2024 period, as illustrated in Fig.1.

Geographic Distribution Analysis

As illustrated in Fig. 2, the spatial distribution of research on shading systems over the past two decades

Table 1. Bibliographic Metadata and Analytical Parameters of Reviewed Studies. Source: Authors.

No.	Title	Methodological Approach	Key Parameters	Authors
1	Multi-objective energy and daylight optimization of amorphous shading devices in buildings	Performance-based multi-objective optimization	Daylighting, energy savings	Kirimtat et al. (2019)
2	Deployable kinetic shading device via 3D printing and alternative actuators: Application of shape memory alloys (SMA) for reactive and climate-responsive architecture	Design, simulation, and prototyping	Illumination, 3D printing, shape memory alloys	Yi et al., 2020
3	Enhancing thermal and visual comfort in glazed buildings through shading systems	Simulation-based research	Thermal and visual comfort, daylighting, uniformity	Evola et al. (2017)
4	Impact of solar shading on energy needs in free-standing office buildings in Italian climates	Dynamic simulation-based study	Heating, cooling, lighting, and energy efficiency	Bellia et al. (2013)
5	Simulation-based design of a healing environment for ICUs: Optimizing daylight and view access in a temperate climate—case study from Palestine	Simulation-based research	Optimization, daylighting, visual access, cooling, and heating load reduction	Amleh et al. (2023)
6	Simulation-based analysis of vertical shading devices for improving thermal performance in residential buildings (Case study: New Asyut City)	Simulation-based study	Thermal performance, vertical shading evaluation	Ali (2012)
7	Daylighting and shading control for energy conservation in fully glazed offices in hot climates	Mixed-method: simulation and experimental validation	Daylighting, DGI index, energy savings, orientation, temperature, glare	Al Touma & Ouahrani, (2017)
8	Energy impact of louvered shading devices	Parametric and simulation-based study	Façade orientation, geographical latitude, thermal comfort, energy	Palmero-Marrero & Oliveira (2010)
9	Comparative performance analysis of daylight and energy efficiency in double-skin façades with multisectional shading systems and control strategies	Simulation-based study	Daylighting, thermal performance	Hong et al. (2022)
10	Energy simulation of glazed office buildings in Sweden	Simulation-based research	Thermal comfort, energy use, open-plan vs. cellular offices, window-to-wall ratio (WWR)	Poirazis et al. (2008)

Table 2. Technological, Typological, and Climatic Contexts of Reviewed Studies. Source: Authors.

No.	Software Used	Shading Device Type	Building Typology	Geographic Location	Climate Type (Köppen Classification)
1	EnergyPlus	Amorphous shading devices	Office	Turkey	Csa, Cfb, BSh, BSk
2	DIVA, EnergyPlus, Rhino, Grasshopper, Radiance	Kinetic	Responsive building envelope	USA	Cfa, Csa, Af
3	EnergyPlus	Reflective coatings / Movable	Office	Italy	Csa, Cfb
4	EnergyPlus (Dynamic simulation)	Solar shading (Louvers, Overhangs)	Office	Italy	Csa, Cfb
5	DesignBuilder	Horizontal and vertical elements	Healthcare	Palestine	Csa, BSh
6	TAS	Louvers	Residential	Egypt	BWh
7	EnergyPlus	Blinds, brise-soleil (louvers)	Office	Qatar	BWh
8	TRNSYS, EES	Louvers	Multi-zone shared thermal space	Mexico, Egypt, Portugal, Spain, UK	Aw, BWh, Csa, Cfb
9	EnergyPlus, Radiance	Multisectional systems (Rollers, Blinds)	Double-skin façade	China	Cfa, Dwa
10	IDA ICE, Parasol	Intermediate venetian blinds, internal screens, fixed external louvers	Office	Sweden	Cfb, Dfb

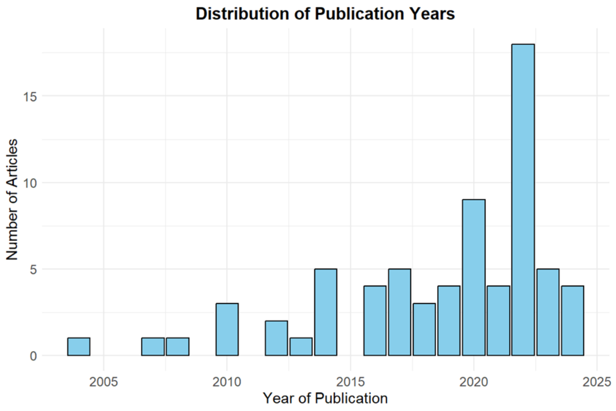

Fig. 1. Temporal Distribution of Reviewed Articles (2004–2024). Source: Authors.

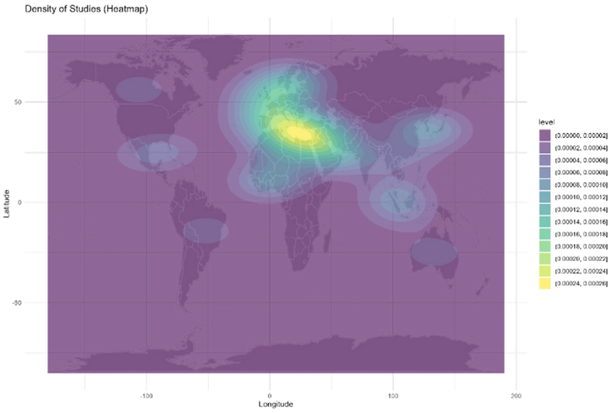

Fig. 2. Geographic Distribution of Reviewed Articles. Source: Authors.

reveals a pronounced geographical concentration. The Middle East, Iranian Plateau, and Eastern Mediterranean highlighted in yellow and light green hues account for approximately 60–70% of the reviewed studies. This high concentration is directly linked to the prevalence of hot-arid climates in these regions and the pressing need for solar radiation control in architectural design. Following this, Southeast Asia and parts of Central Europe represent the second cluster of research activity, contributing roughly 20–25% of the studies. In these areas, rapid urban development and stringent climatic design requirements have driven scholarly engagement. In contrast, North America, Latin America, and the Saharan regions of Africa, depicted in dark blue and purple, comprise less than 10% of the literature. Notably, polar regions, Oceania, and Australia are virtually absent from the reviewed corpus, indicating either a lack of climatic necessity or reduced academic focus on solar-shading strategies in those geographies

Climatic Frequency Analysis

Fig. 3, which illustrates the climatic distribution of shading-related studies based on the Köppen–Geiger climate classification, offers a clear visualization of the frequency of research across various climate types. The hot desert climate (BWh) dominates the corpus with more than 17 studies, represented in light green. This prominence is unsurprising given the extreme solar irradiance and elevated ambient temperatures characteristic of such regions, underscoring the critical demand for solar control solutions. Trailing closely are the temperate oceanic (Cfb) and hot-summer Mediterranean (Csa) climates, with approximately 13 to 15 studies each, shown in green and blue-green hues. These climate zones, marked by warm summers and abundant natural light, exhibit consistent demand for shading interventions to maintain thermal and visual comfort. The hot semi-arid climate (BSh) also occupies a significant share of the literature, with 12– 13 studies, while the humid subtropical climate (Cfa), represented by around 11 cases, highlights the intricate challenges of managing heat and moisture simultaneously in hot-humid environments. Moderate research attention has been devoted to tropical rainforest (Af), tropical savanna (Aw), and humid continental climates with hot summers (Dwa), each accounting for 8– 10 studies. These findings indicate a growing interest in hybrid or adaptive shading strategies suited to dynamic thermal and moisture

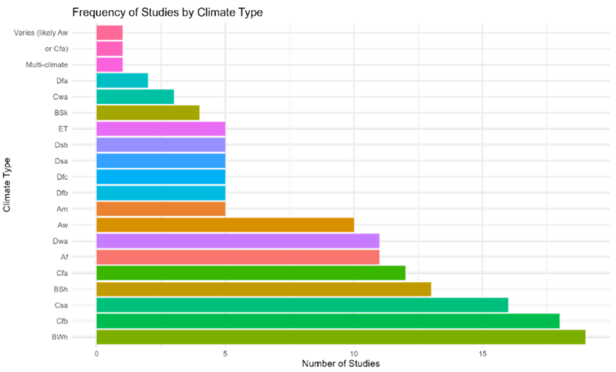

Fig. 3. Frequency of Studies Across Köppen–Geiger Climate Zones. Source: Authors.

regimes. By contrast, colder climate zones such as Dfb (humid continental, warm summer), Dfc (subarctic), and Dfa (humid continental, hot summer) exhibit lower frequencies (5– 7 studies), reflecting a relatively diminished demand or different performance priorities in these contexts. Finally, climates such as tundra (ET), cold semi-arid (BSk), and mixed or transitional zones, with only 1 to 3 studies, are depicted in light purple tones revealing substantial research gaps in cold, highly variable, or underexplored regions. This pattern highlights key opportunities for future investigations into shading performance under extreme or atypical climatic conditions.

Analysis of Simulation Software Used in the Reviewed Literature

An evaluation of simulation tools employed across the reviewed studies reveals that EnergyPlus stands out as the most frequently used building performance modeling software, featuring in approximately 9.2% of the studies. Its widespread adoption reflects its high precision and robustness in simulating heating, cooling, and energy consumption, making it a preferred choice for energy-centric analyses. In the domain of daylight simulation, Radiance and Daysim each appear in 3.8% of the studies. Their established reliability in modeling natural illumination and conducting comprehensive daylighting assessments grants them a specialized role in visual performance evaluation. Other tools, such as Ecotect, DesignBuilder, and Honeybee, each accounting for between 3.1% and 3.8% are favored for their user-friendly interfaces, intuitive visualization capabilities, and broad multi-domain functionality, which appeal to both novice and expert users in architectural simulation. Notably, plug-ins integrated within Grasshopper, such as Ladybug and Honeybee, are increasingly utilized in parametric and performance-driven design workflows, enabling flexible and iterative design exploration within Rhinoceros 3D environments. While these tools are gaining traction, more specialized platforms such as Octopus (used for evolutionary optimization) and Parasol (tailored to façade control systems) remain underrepresented, with less than 1% adoption across the dataset. Fig. 4 illustrates the relative frequency of simulation software employed in the selected body of literature.

Research Trends by Building Typology

An analysis of building types examined in the reviewed studies reveals a distinct typological focus. Office buildings, representing approximately 35% of the total sample, dominate the scholarly discourse. This prevalence reflects their significant contribution to energy consumption in the built environment and the corresponding urgency to optimize their environmental performance. Residential buildings follow with a 9.9% share, highlighting the growing recognition of energy efficiency imperatives in the housing sector. Educational facilities—particularly classrooms—alongside specialized spaces such as hospitals and libraries, constitute the next tier of interest. Although these categories are less frequently represented, they offer fertile ground for innovative and context-sensitive shading strategies. Notably, a smaller yet important body of research has explored advanced architectural typologies, including double-skin façades and fully glazed buildings. These studies reflect a movement toward high-performance envelope systems that demand precise shading integration. The distribution of research across building types underscores the field's growing emphasis on contextual design, tailoring shading solutions to the distinct functional and thermal-

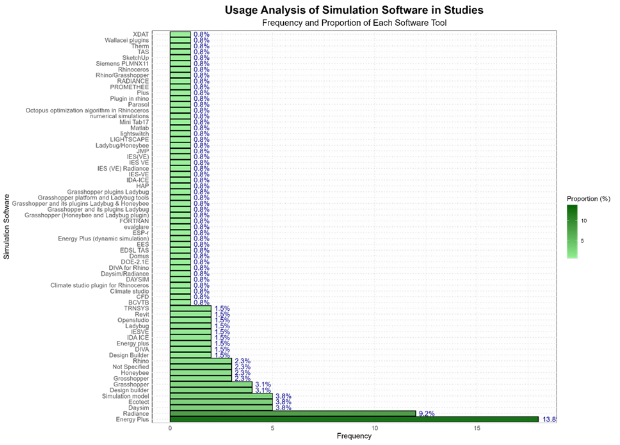

Fig. 4. Frequency of Simulation Tools Used in the Reviewed Articles. Source: Authors.

lighting needs of different spaces. The diversity of typologies represented—ranging from single-zone structures and mixed-use buildings to retrofitted office blocks and net-zero attic spaces—further reflects the multifunctional challenge facing contemporary shading design. Table 3 summarizes the frequency of studies by building type, along with corresponding article references, listed according to their numbering in the reference section.

Research Trends Based on Shading Device Typologies

An analysis of shading system types across the reviewed literature highlights distinct preferences aligned with performance objectives and technological trends. External shading devices (ESDs) emerge as the most commonly investigated typology, featuring in 15.5% of the studies. Their widespread adoption is attributed to their proven effectiveness in controlling direct solar radiation before it penetrates the building envelope. Photovoltaic shading devices (PVSDs) follow, accounting for approximately 10% of the reviewed cases. These systems combine solar control and on-site renewable energy generation, offering a dual-function solution for sustainable building design. Louver systems also hold a prominent position (8.5%) due to their geometric adaptability and capacity to regulate both solar gains and natural ventilation across various climatic conditions. Dynamic and automated shading systems, while currently underrepresented (less than 5%), are gaining traction as part of a forward-looking shift toward intelligent façades. These systems leverage environmental sensors and control algorithms to optimize internal environmental conditions in real-time, aligning with the evolution of responsive and performance-driven design paradigms. A broader range of hybrid and experimental shading typologies, including internal blinds (vertical and horizontal), kinetic systems, roller shades, light shelves (LSS), and composite systems, appeared in a small number of studies. These reflect ongoing attempts to integrate architectural expression with energy performance and user-centric design objectives. Table 4 presents the frequency of different shading device types along

Table 3. Frequency of Building Typologies Investigated in Reviewed Studies. Source: Authors.

Building Typology	Frequency	Article Numbers (as per reference list)
Office buildings	25	Abdou et al., 2022; Ahadi, 2022; Al-Masrani et al., 2018; Alsukkar et al., 2022; Alwetaishi et al., 2021; Bessoudo et al., 2010; Bhatia et al., 2019; Buratti et al., 2022; Cho et al., 2014; Chou et al., 2016; Da Silva & Veras, 2023; Dabaj et al., 2022; De Luca et al., 2022; Dutta et al., 2017; Edupuganti, 2013; Esfandiari et al., 2024; Jiang et al., 2024; Kalaimathy et al., 2023; Karlsen et al., 2016; Keshtkar Ghalati & Ahmadian, 2024; Khidmat et al., 2022; Kirimtat et al., 2016; Knudsen & Petersen, 2020; Lau et al., 2016; Mandalaki et al., 2012; Mousavi et al., 2025
Residential buildings	7	Bellia et al., 2013; de Almeida Rocha et al., 2020; Heidari et al., 2021; Mangkuto et al., 2019; Manzan & Clarich, 2017; Motlagh et al., 2024; Nazari et al., 2023
Single-room spaces	5	Datta, 2001; Alsharif et al., 2023; Fouad et al., 2019; Kirimtat et al., 2019; Mendis et al., 2020
Classrooms	4	Khidmat et al., 2022; Kitsopoulou et al., 2024; Lai et al., 2017; Li et al., 2019
High-rise office buildings	3	Esfandiari & Shokri, 2023; Mangkuto et al., 2019; Nicoletti et al., 2023
Miscellaneous/Unclassified types (e.g., double-skin façades, multi-storey hotels)	2	Hamza et al., 2022; Hashemi, 2014; Cho et al., 2014; Al Touma & Ouahrani, 2017; Evangelisti et al., 2020; Hoffmann et al., 2016
Other unique cases (e.g., single-zone buildings, mixed-use buildings, retrofitted offices, fully glazed façades, transparent domes, municipal buildings, ICU units, kinetic buildings, net-zero energy attic space)	1 each	Aketouane et al., 2018; Alhuwayil et al., 2019; Ali, 2012; Al-Masrani & Al-Obaidi, 2019; Gomes et al., 2022; Ito & Lee, 2024; Koç & Kalfa, 2021; Mohammed et al., 2022; Park et al., 2020; Samadi et al., 2019; Sern et al., 2022; Skarning et al., 2017; Sorooshnia et al., 2025; Stamatakis et al., 2016

Table 4. Frequency of Shading Device Types in Reviewed Studies. Source: Authors.

Shading Device Type	Frequency	Article Numbers (as per reference list)
External Shading Devices (ESDs)	11	Bessoudo et al., 2010; Dabaj et al., 2022; Kirimtat et al., 2019; Lau, Salleh et al., 2016; Mangkuto et al., 2019
Photovoltaic Shading Devices (PVSDs)	7	Ahadi, 2022; Alsukkar et al., 2022; Alwetaishi et al., 2021; Fouad et al., 2019; Karlsen et al., 2016; Mangkuto et al., 2019
Louver Systems	6	Alsharif et al., 2023; Bellia et al., 2013; Bessoudo, 2010; Hashemi, 2014; Keshtkar Ghalati & Ahmadian, 2024
Dynamic Systems / Venetian Blinds	3	Evangelisti et al., 2020; Dutta et al., 2017; De Almeida Rocha et al., 2020; Knudsen & Petersen, 2020; Mendis et al., 2020; Nicoletti et al., 2023
Other Shading Devices (e.g., internal blinds, kinetic systems, roller shades, light shelves)	2	Alhuwayil et al., 2019; Bhatia et al., 2019; Gomes et al., 2022; Koç & Kalfa, 2021; Li et al., 2019; Lim et al., 2020; Mohammed et al., 2022
Diverse / Composite Configurations (e.g., amorphous shading, automated louvers, hybrid systems, PCM-integrated devices, sun-tracking mechanisms, multi-sectional rollers, egg-crate systems, overhang–fin–louver combinations, dual-skin façades)	1 each	Abdou et al., 2022; Al-Masrani & Al-Obaidi, 2019; Al-Masrani et al., 2018; Cho et al., 2014; Da Silva & Veras, 2023; de Almeida Rocha et al., 2020; Evangelisti et al., 2020; Kalaimathy et al., 2023; Ito & Lee, 2024; Jiang et al., 2024; Hamza et al., 2022; Mandalaki et al., 2012; Manzan & Clarich, 2017; Nicoletti et al., 2023

with their corresponding article references, categorized according to the reference numbering in the study.

Methodological Approaches in the Reviewed Literature

A critical examination of the methodological orientations across the reviewed studies reveals a strong dominance of simulation-based research, which accounts for approximately 20% of the total corpus. These studies predominantly rely on dynamic and thermal modeling to evaluate the performance of shading systems under various environmental and design conditions. A notable subset of the literature integrates simulation with experimental data, enhancing model calibration and ensuring greater alignment between simulated results and real-world conditions. This hybrid approach reflects an effort to bridge the gap between theoretical modeling and practical application. Furthermore, there is an emerging body of work centered on single- and multi-objective optimization, comprising roughly 8.4% of the studies. These works aim to balance competing objectives such as energy savings, daylight availability, and economic feasibility, often employing evolutionary algorithms or parametric tuning for performance enhancement. Parametric design, often in combination with simulation platforms (e.g., Rhino, Grasshopper, Honeybee), is gaining momentum as well, with approximately 4–5% of studies leveraging algorithmic modeling to explore a wider solution space for shading configuration and control (Table 5). Although qualitative and observation-based methodologies remain underrepresented, the growing incorporation of machine learning and data-driven frameworks indicates a shift toward user-centric, adaptive systems. These advancements hold promise

Table 5. Frequency of Methodological Approaches in the Reviewed Studies. Source: Authors.

Methodological Approach	Frequency	Article Numbers (as per reference list)
Simulation-based research	14	Bedon et al., 2018; Al Dakheel & Tabet Aoul, 2017; Al-Masrani et al., 2018; Evangelisti et al., 2020; Evola et al., 2017; Fouad et al., 2019; Hamza et al., 2022; Koç & Kalfa, 2021; Lim et al., 2020; Mangkuto et al., 2019; Manzan & Clarich, 2017
Hybrid simulation and experimental research	5	Da Silva & Veras, 2023; Dabaj et al., 2022; Dutta et al., 2017; Kalaimathy et al., 2023
Simulation-based optimization research	4	Khidmat et al., 2022; Bhatia et al., 2019; Motlagh et al., 2024
Simulation combined with economic analysis, dynamic simulation, multi-objective optimization, or parametric modeling	2	Alwetaishi et al., 2021; Ali, 2012; Keshtkar et al., 2024; Khidmat et al., 2022; Khidmat et al., 2022; Mohammed et al., 2022; Park et al., 2020
Composite and advanced approaches (e.g., integrated frameworks combining simulation with field calibration, parametric design, machine learning, regression analysis, or MCDM)	1 each	Theodoropoulou et al., 2024; Tzempelikos & Athienitis, 2007; Wang et al., 2020; Wong & Istiadji, 2004; Wu & Zhang, 2022; Yao, 2014; Ye et al., 2016; Yi et al., 2020; Yin & Muhieldeen, 2024; Yun et al., 2014; Ziaee & Vakilinezhad, 2022; Zoure & Genovese, 2023; Sern et al., 2022; Skarning et al., 2017; Sorooshnia et al., 2025; Stamatakis et al., 2016; Rabani et al., 2021; Sabbagh et al., 2022; Samadi et al., 2019; Sendi, 2014

for future studies that aim to model real occupant behavior, validate system performance in situ, and support the development of smart, responsive façades.

Keyword Content Analysis: Dominant Themes and Research Gaps

A content analysis of the most frequently occurring keywords in the reviewed literature on shading systems reveals three dominant thematic clusters: energy consumption reduction, thermal comfort enhancement, and daylighting optimization. The prevalence of terms such as “energy savings” and “UDI” (Useful Daylight Illuminance) reflects the field’s quantitative and data-driven orientation, where computational simulations and performance metrics are prioritized over qualitative or experiential dimensions. Although terms associated with parametric design and multi-objective optimization are present in the corpus, their relative frequencies remain substantially lower than those of more conventional energy metrics, such as “cooling energy demand” or “illuminance level.” This indicates a gradual but incomplete transition from single-objective engineering models toward more complex and integrated design-evaluation paradigms. More critically, the absence or underrepresentation of keywords such as “user preferences” and “post-occupancy evaluation” points to a significant research gap. While recent studies exhibit high levels of technical precision and simulation rigor, they often lack a robust engagement with the human-environment interaction dimension of shading system performance. This disconnect underscores the need for complementary user-centered research, particularly in the domains of adaptive behavior, experiential comfort, and real-world system validation. Fig. 5 presents a word cloud visualization of the dominant performance parameters and thematic emphases identified across the reviewed body of literature.

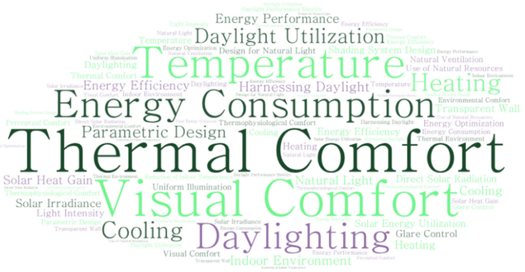

Fig. 5. Dominant Keywords and Performance Parameters in Reviewed Studies (Word Cloud). Source: Authors.

Climatic Classification Analysis of Shading Systems

A systematic analysis of the reviewed data underscores a critical insight: climatic diversity from tropical rainforest (Af) to tundra (ET) zones necessitates highly adaptive and context-specific shading strategies. In hot-humid climates (e.g., Cfa and Aw), technologies such as dynamic shading systems and photovoltaic louvers are widely implemented to reduce cooling loads while contributing to on-site renewable energy generation. Conversely, in colder climates (e.g., Dfb, Dfc, ET), solutions such as light shelves, internal roller blinds, and other high-transmittance systems are employed to maximize daylight penetration and minimize heat loss, particularly during low-sun winter periods. This spectrum of shading responses highlights the fact that shading is not a static or standalone technical intervention, but rather a flexible and integrative system that must align with building morphology, programmatic function, and localized climatic parameters. The integration of advanced technologies in high-rise buildings within tropical zones reflects an ongoing paradigm shift toward multi-objective, hybrid, and climate-responsive design solutions. In cold and semi-arid climates, greater emphasis is placed on optimizing the window-to-wall ratio (WWR) and enhancing passive daylighting, balancing solar access with thermal conservation. Overall, the effectiveness of shading systems is contingent upon the development and application of a comprehensive and adaptive framework, one capable of simultaneously addressing climatic complexity, functional performance, and perceptual comfort. Fig. 6 illustrates a systematic classification of shading devices according to climate zone, geographic location, building typology, and performance criteria.

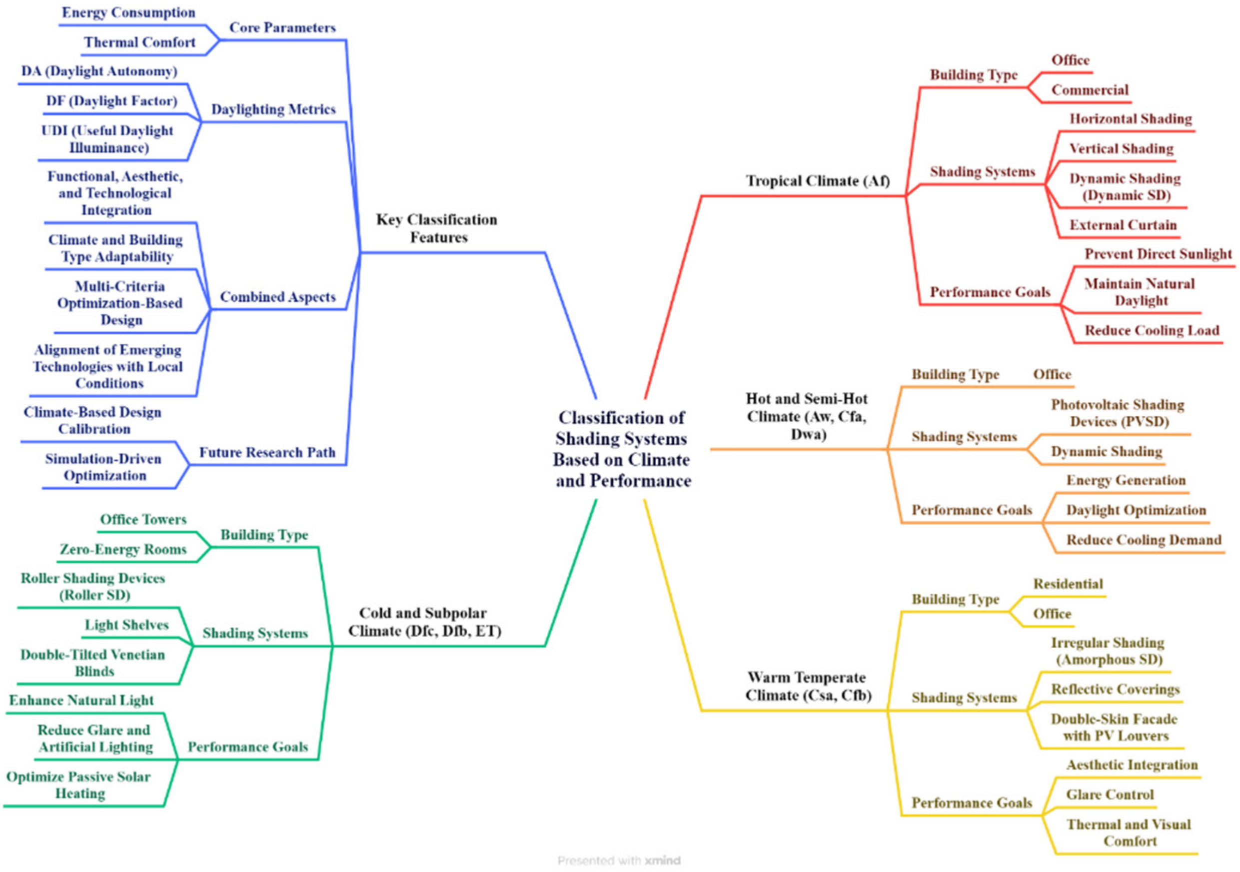

Fig.6. Systematic Classification of Shading Devices by Climate Type, Geographic Region, Building Use, and Functional Performance. Source: Authors.

Discussion

The findings of this study indicate that despite notable advancements in the design and simulation of architectural shading systems, a substantial proportion of existing research, over two-thirds of the 70 reviewed articles remains confined to single-objective approaches, typically focused on energy savings or glare control (Al-Tamimi et al., 2011; Dubois, 2001). While such approaches have proven effective in hot and arid climates, where solar radiation control is a priority (Buratti et al., 2022; Lai et al., 2017), they often fall short in addressing multi-dimensional occupant needs, such as daylight availability, visual comfort, and quality of view (Kim & Kim, 2010; Taveres et al., 2019). In contrast, multi-criteria approaches, though still underrepresented, have demonstrated superior environmental and perceptual performance by integrating functional, aesthetic, and climatic considerations within the design process (Alsharif et al., 2023; Hafez et al., 2023). In temperate and semi-arid climates, recent research suggests that deploying integrated shading strategies can simultaneously preserve daylight quality, reduce energy expenditures, and enhance user satisfaction (Palmero-Marrero & Oliveira, 2010). Nevertheless, the application of parametric models, intelligent algorithms, and automated optimization systems remains limited. This limitation is largely attributed to computational complexity, implementation costs, and the scarcity of long-term field data (AbdelAziz, 2016; Al Dakheel & Tabet Aoul, 2017). Only a handful of studies have investigated adaptive design frameworks capable of responding to dynamic environmental conditions and user behavior (Freewan, 2014; Alsharif et al., 2023). However, challenges such as maintenance requirements, systemic complexity, and lack of empirical validation continue to hinder their widespread adoption (Bellia et al., 2014; Edupuganti, 2013). From a climatic perspective, the literature is heavily skewed toward hot-arid (BWh) and Mediterranean (Csa) climates, where high solar exposure and cooling demands dominate building performance concerns (Buratti et al., 2022). In contrast, cold climates (Dfb, Dfc) are significantly underrepresented, despite the fact that design goals in these regions revolve around heat retention and daylighting enhancement domains in which systems such as light shelves and internal roller blinds have shown high potential (Dubois, 2001; Prieto et al., 2018). On the technological front, innovations such as photovoltaic louvers and electrochromic glazing present promising synergies between solar control and clean energy generation (Ma et al., 2023). However, empirical evidence on their durability, real-world performance, and behavioral impact remains sparse (Edupuganti, 2013). Moreover, topics such as embodied carbon, energy payback, recyclability, and life-cycle assessment (LCA) of materials are largely neglected in current research (Bellia et al., 2014; Hafez et al., 2023). In response to the first research question, findings clearly demonstrate that an effective classification of shading systems must be grounded in a structured framework that accounts for climate, building type, technology, human factors, and environmental behavior (Datta, 2001). Reliance on a single performance index will inevitably result in suboptimal and cost-ineffective design outcomes (Alsharif et al., 2023). Regarding the second research question, the proposed framework in this study comprises three core layers:

1.Advanced modeling and multi-criteria simulation,

2.Parametric optimization grounded in real-world constraints, and

3.A feedback-driven design–implementation–evaluation cycle supported by sensor data and user experience (Freewan, 2014; Al Dakheel & Tabet Aoul, 2017).

This framework enables a transition from conventional shading practices to adaptive, ecologically sustainable, and human-centered solutions. To advance future research and practice in this domain, the following four strategic priorities are recommended:

1.Development of user-centered models that account for behavioral patterns and cultural context;

2.Integration of advanced optimization algorithms into design processes;

3.Comprehensive life-cycle assessment of technologies and materials, including their environmental impact and recyclability;

4.Execution of longitudinal field studies to validate system performance under real-use conditions.

Only through such a holistic and interdisciplinary approach can the next generation of shading systems deliver simultaneously on the promises of energy efficiency, environmental quality, and architectural sustainability.

Conclusion

The results of this study reveal that despite the growing quantitative and qualitative advancements in the field of architectural shading systems, significant challenges persist—particularly the lack of an integrated perspective that simultaneously accounts for climatic, behavioral, and design-related considerations. A systematic review of 70 selected studies demonstrated that the majority of existing approaches remain single-dimensional, primarily emphasizing energy consumption reduction or solar glare control, while often overlooking multi-criteria requirements such as visual comfort and thermophysiological well-being. Moreover, the difficulty of adapting current solutions to cold climates and regions with high thermal variability further underscores the need for more comprehensive and adaptable strategies. In addressing its two central research questions, this study first establishes that an effective classification matrix must integrate at least four key dimensions of climate zone, building typology, shading technology, and multi-performance indicators to avoid generic or inefficient design prescriptions. Second, by critically analyzing prevailing methodologies in simulation, optimization, and field validation, the study proposes an integrated framework that employs a dynamic design–implementation–evaluation loop to continuously calibrate shading performance in real-world contexts. This framework facilitates the integration of user behavior data, climatic realities, and environmental criteria throughout the building lifecycle. At a broader level, it becomes evident that transitioning toward multi-objective, climate-adaptive shading systems requires a transdisciplinary synthesis bridging fields such as energy engineering, thermal simulation, environmental psychology, and architectural design. Future research, particularly those incorporating parametric methodologies, cross-disciplinary optimization techniques, and longitudinal studies on occupant behavior, holds the potential to transcend conventional energy-saving goals. Such work can deliver shading solutions that simultaneously enhance user satisfaction, climatic adaptability, and architectural identity. Ultimately, shading systems must evolve beyond passive protective elements and emerge as active agents in shaping a sustainable and human-centered built environment.

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