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Biomimetic self-shading technology for improving building environmental performance: A bibliometric analysis

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Abstract: Biomimetic self-shading (BSS) technology proposes principles derived from natural systems that can improve a building's energy efficiency, thermal comfort, and environmental performance in hot and dry climates. Based on biological principles observed in nature, this novel approach minimizes energy use and enhances indoor routing parameters. The study aims to review the state of the art in the field of self-shading and its connection with biomimetic science to identify gaps in scientific research. It provides a detailed overview and bibliometric review of BSS, demonstrating its applicability as a morphological approach by investigating building forms and types of self-shading envelopes. The study covers the period from 2014 to 2025, using the Scopus dataset and in-depth analytical tools such as Biblioshiny and VOS Viewer. The results of this review highlight trends in BSS publications and research areas, along with a systematic analysis of BSS design strategies based on the opportunities and challenges of previous studies. The study identifies gaps in the earlier literature, which future studies will address. It confirms that BSS is an effective passive design solution with significant potential for improving environmental performance. Finally, the study concludes with the BSS design strategy to improve environmental performance indicators.

Keywords: *Bibliometric analysis, Biomimetic self-shading (BSS), Biomimetic, Environmental performance, Morphological approach, Passive design, Self-shading.*

1. Introduction

High temperatures and direct solar radiation significantly increase energy consumption in buildings [1, 2], particularly in hot and dry regions, where heat transfer through external walls outpaces that through other building envelope components [3, 4]. To address issues with energy demand, nature provides valuable insights through biomimetic approaches, drawing inspiration from its processes [5, 6], and has recently gained significant attention. By studying organisms' millions of years of evolution to maximize their performance and survival, scientists and engineers can create novel solutions that resemble the elegance and efficiency of the natural world [7-9]. Biomimetic science is an interdisciplinary, multidisciplinary methodology. Its approach presents many barriers that should be studied to translate natural solutions into architectural designs. Thus, understanding biomimetic design principles is of extra importance [10-13] as illustrated in Figure 1.

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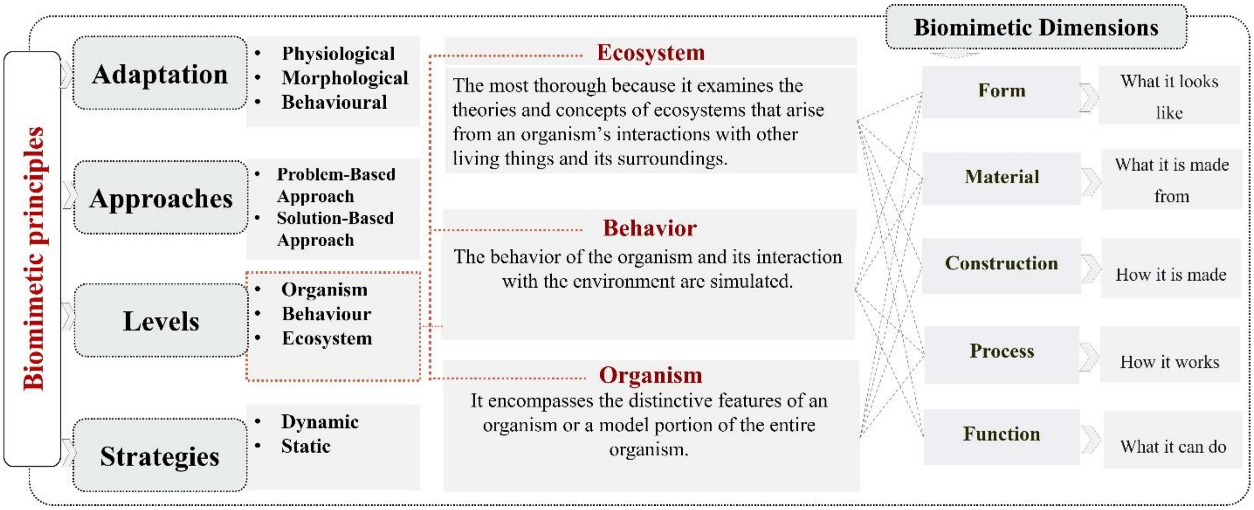

Figure 1.
Biomimetic principles.
Source: The authors based on Verbrugghe, et al. [12] and Al-Obaidi, et al. [13].

One of the fields where the biomimetic approach has shown immense potential is the creation of self-shading buildings [14-18]. In hot and dry climates, excessive sun can cause glare and increase the energy needed for cooling, making indoor spaces uncomfortable [2, 19-23]. However, scientists have identified self-shading as an effective passive design strategy [24] that enhances environmental performance indicators in buildings [25-27] by examining how plants and animals adapt to these environments [8, 28-30]. BSS's design strategy aims to develop a nature-inspired shading system. This approach minimizes solar heat gain by incorporating a biomimetic morphological method for self-shading [13, 31, 32]. The study aims to review the state of the art in the field of self-shading and its connection with biomimetics to identify gaps in scientific research. It is structured as follows: Section 1 provides an introduction; Section 2 outlines the data collection methods and tools used in the bibliometric analysis. Section 3 analyzes growth trends, revealing an inadequate connection between biomimetic design and self-shading, despite their importance. Section 4 discusses the biomimetic morphological approach to self-shading. It examines previous results on identified opportunities and challenges and presents environmental performance improvement indicators and ways to calculate them. It identifies the gaps that require further research and concludes with a proposed strategy for designing BSS buildings. Finally, Section 5 presents the conclusions. Figure 2 illustrates this research's methodological framework and structure.

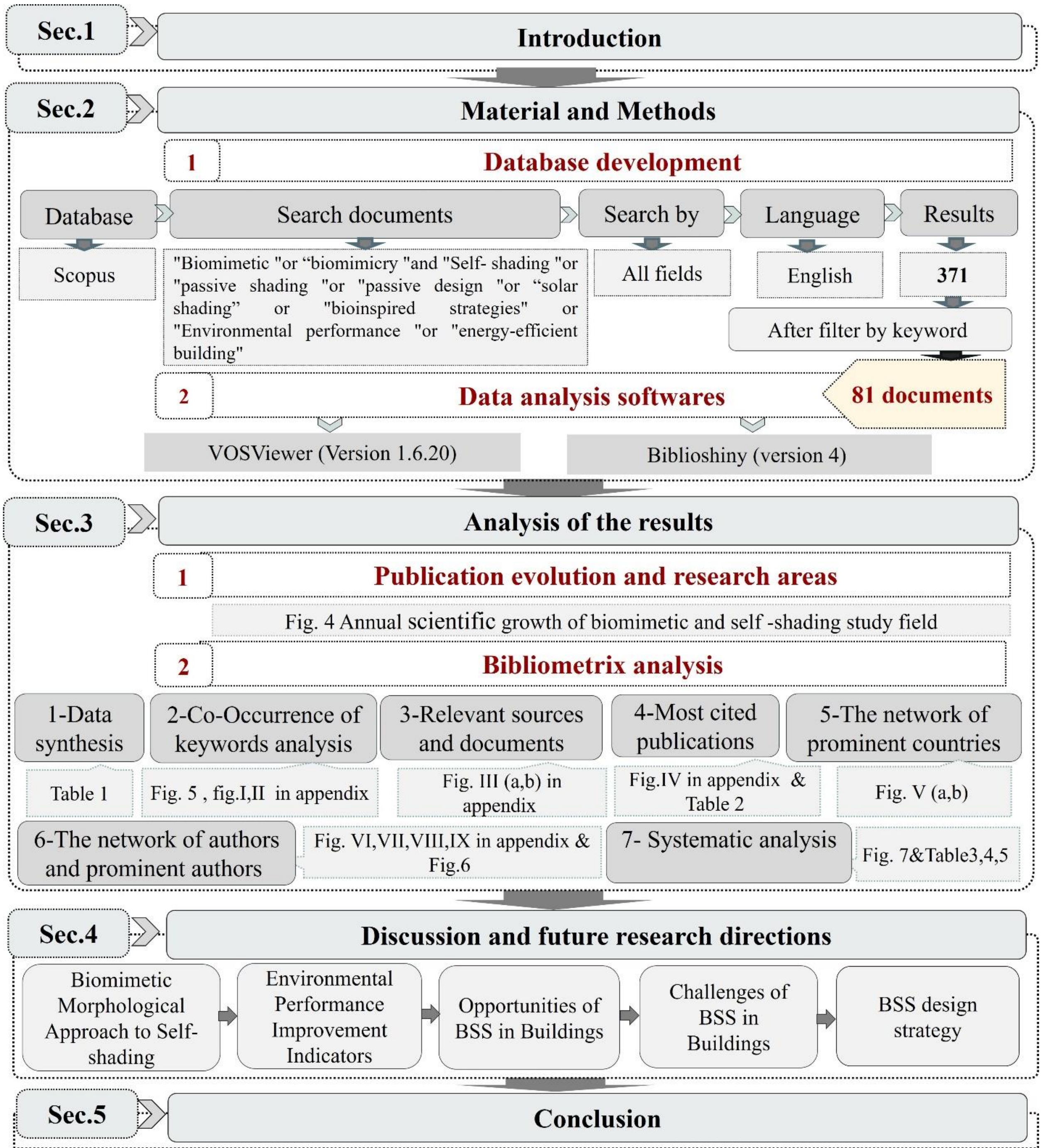

Figure 2.
A graphical representation of the methodological framework.
Source: Authors own creation.

2. Materials and Methods

This section outlines the data collection method for biomimetic and self-shading publications and the tools used in the bibliometric analysis.

2.1. Database Development

The review consists of two main components: bibliometric and systematic analyses. The Scopus database is utilized for the search due to its collection of studies on subjects compared to databases like the Web of Science [33]. This section presents the inclusion and exclusion criteria of the papers summarized for this study. Carefully chosen terms are included in the systematic bibliographic search query to yield all potential literature related to the designated topic. The following sections provide more details about these steps, as shown in Figure 3.

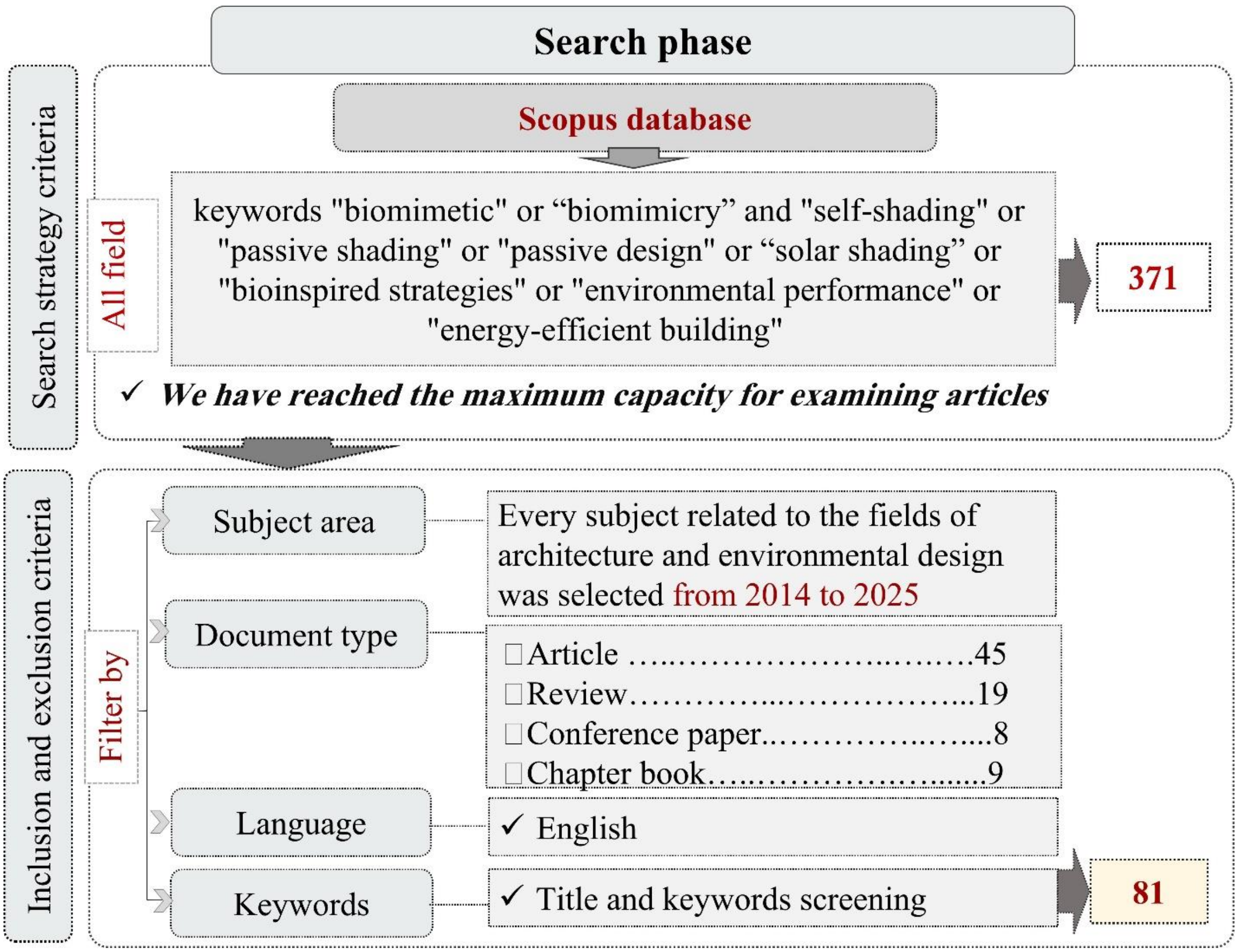

Figure 3.
Systematic literature review flowchart.
Source: The authors based on the Scopus dataset

They describe the method for collecting data on biomimetic and self-shading publications and the tools used for bibliometric analysis. A bibliometric analysis was conducted to assess the literature on BSS strategy. The Scopus database was utilized, and tools such as Biblioshiny and VOSviewer were employed to visualize the existing literature. A network map was generated to illustrate the connections among the selected papers. Use the All-Fields analysis to search for documents related to the keywords "biomimetic" or "biomimicry" and "self-shading" or "passive shading" or "passive design" or "solar shading" or "bioinspired strategies" or "environmental performance" or "energy-efficient building" in (all fields) with the selection of the English language and the subject areas related to the search words

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only. This search returned 371 documents on 2 February 2025, and the selected database was reviewed, which deepened the focus areas to reach 81 documents.

The study excluded publications in languages other than English and keywords irrelevant to the topic area. The research encompassed a broad temporal range, without specific time constraints. It also excluded results from research fields such as chemical and agricultural engineering. Consequently, the study identified a significant gap in the limited research on self-shading and its connection to biomimetic science. The selected documents were saved in CSV format to facilitate bibliometric analysis.

2.2. Selection of Tools for Data Analysis

Over the past two decades, many software tools have been developed to aid in scientific mapping and bibliometric analysis. While these tools differ in design and function, they share a common objective: to uncover the relationships among key entities in research disciplines, such as keywords, documents, authors, references, and journals [34, 35]. The research used bibliometric analysis via the bibliometric R package (version 4) [36] and VOS viewer (version 1.6.20) [37] to analyze data and visualize the interconnections among these entities.

3. Analysis of Results

The results offer a comprehensive view of the bibliometric analysis, including co-occurrence analysis, author keywords, authors, journals, bibliographic coupling, and co-citation analysis. Each aspect of the results has been examined to present valuable information on research advancements, trends, and developments in BSS strategy.

3.1. Publication Evolution and Research Areas

Limited research has been conducted regarding the scope of the study over time since 2014, as illustrated in Figure 4. The development of publications over the years reveals that during the initial phase, from 2021 to 2024, some publications explored the connection between biomimetic and self-shading technology, primarily focusing on active rather than passive design [1, 3, 21, 27, 38-40]. This observation suggests that this field is still under study and research.

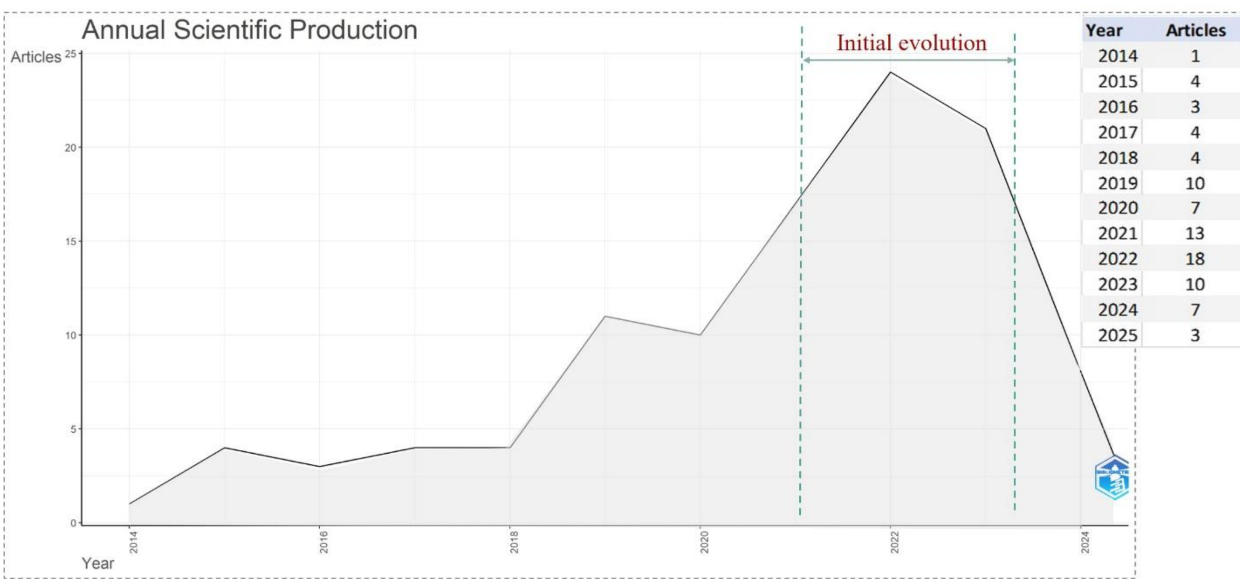

Figure 4.
Annual scientific growth of the biomimetic and self-shading study field.
Source: Based on the Biblioshiny tool.

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3.2. Overall Bibliometric Analysis

The findings in this section cover: (1) the growth and trends of research on biomimetic and environmental performance, (2) scholars, affiliations, and active social networks, and (3) the role of biomimetic and self-shading in promoting environmental performance.

3.2.1. Data Synthesis

Table 1 presents a comprehensive summary of the data synthesis, offering key information and a succinct overview of the dataset that has been published. The table reveals the number of document types in the collected data. The most common document types are article papers (n = 45) and review documents (n = 19). The analysis showed that the time range of publications was from 2014 to 2025. In this study, author keywords and Keywords Plus play distinct roles in categorizing research content. Most of these articles were about biomimetic, adaptive facades and solar shading.

Table 1.
Data synthesis provides essential information and a concise dataset overview.

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2014:2025
Sources (Journals, Books, etc.)	48
Documents	81
Annual Growth Rate %	21.48
Document Average Age	3.52
Average citations per doc	16.85
References	6480
DOCUMENT CONTENTS	
Keywords Plus (ID)	491
Author's Keywords (DE)	304
AUTHORS	
Authors	209
Authors of single-authored docs	9
AUTHORS COLLABORATION	
Single-authored docs	11
Co-Authors per Doc	3.26
International co-authorships %	33.33
DOCUMENT TYPES	
article	45
review	19
book chapter	9
conference paper	8

Source: The authors used the Biblioshiny tool.

3.2.2. Co-Occurrence of Keywords Analysis

Keyword analysis is a crucial bibliographic tool that helps identify key research areas within different specializations [41]. So, linking keywords to the main content of publications is essential for discovering trends in research subjects [42]. This research found that the authors predominantly utilized the keywords "biomimetics," "energy utilization," and "building envelopes." Additionally, we observed that the studies primarily focus on AD strategies to enhance energy performance in building envelopes. Regarding co-occurrence analysis, this analysis is based on the 90 most frequent keywords, as shown in Figure 5.

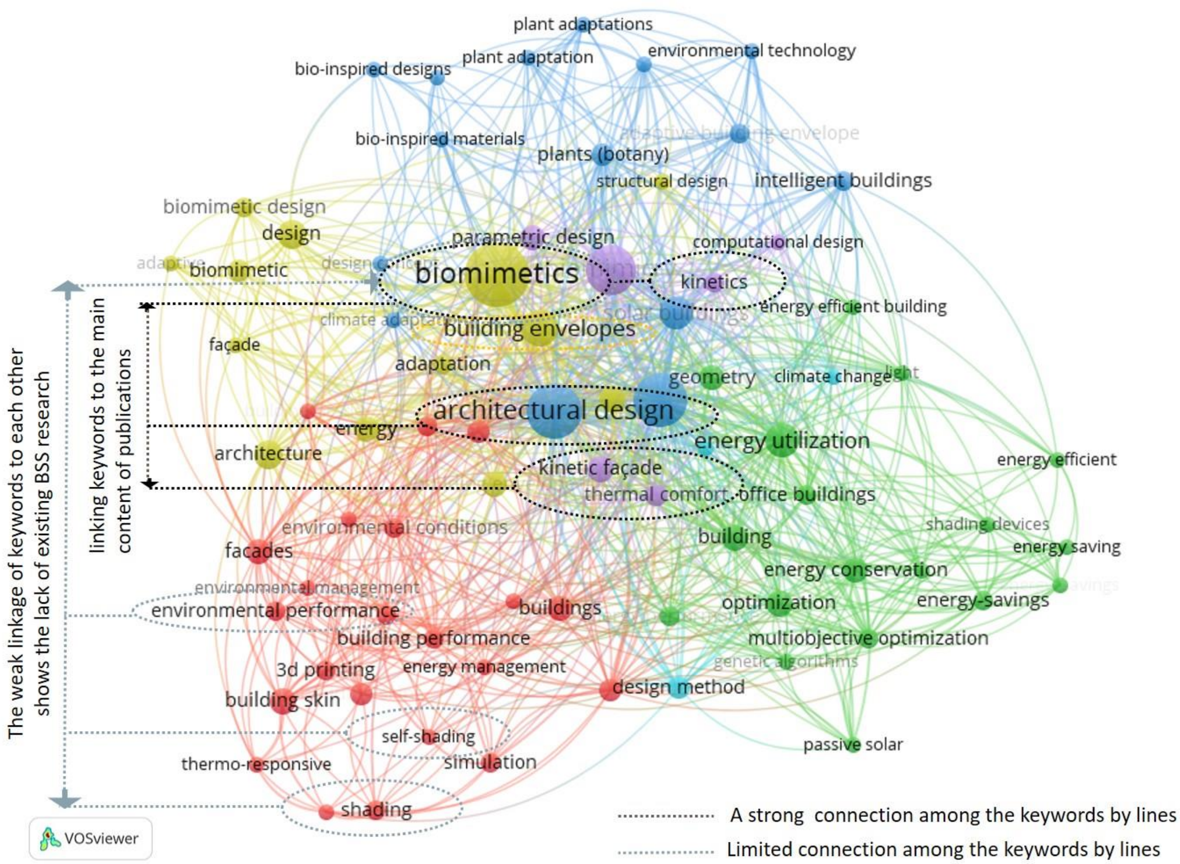


Figure 5.
A network map of keywords during the period (2014–2025): Co-occurrence analysis of keywords with their different clusters.
Source: Based on the Scopus dataset using Vos viewer software.

Eight keywords with a frequency greater than 30 are as follows: “energy efficiency,” “biomimetics,” “building envelopes,” “architecture design,” “thermal comfort,” “performance,” “kinetic facades,” and “environment management.” Six clusters were obtained using VOSviewer, where keywords are represented as nodes; the node size indicates the frequency of the keywords, and the thickness of the connecting lines illustrates the strength of co-occurrence between keywords. The first group (red) primarily focuses on designing adaptive facades with shading systems to achieve thermal comfort and environmental performance. The second group (green) is based on designing building envelopes, while the third (blue) and fourth (yellow) groups consist of keywords related to adaptation design tools. The fifth group (purple) pertains to biomimetic kinetic facades and parametric design, and the sixth group (light blue) relates to adaptive strategies.

The keywords in the first group are "building skin," "shading system," "thermal comfort," and "environmental performance," which are closely related to the keywords "energy efficiency," "sustainable development," and "shading devices" in the second group and "design method" in the sixth group. In contrast, it is weakly related to biomimetic science in the fourth group. The keywords in the fourth group are "biomimetic design," "facades," and "energy," which are closely related to the keywords "architecture design," "adaptive building envelope," and "bio-inspired design" in the third group, and "biomimicry," "kinetic facades," "parametric design," and "thermal comfort" in the fifth group, and "climate change" in the sixth group. The analysis in Figure 5 reveals that the most frequently used and spread keywords related to biomimetic science are closely linked to the design of kinetic or adaptive facades. In contrast, the connection of the words associated with biomimetic science with self-shading in the first group is weak. This indicates that the connection between self-shading and biomimetic science is an emerging topic that should be focused on, unlike kinetic facades and adaptive facades.

Based on the relevance in research fields, the thematic map organizes authors' keywords into four quadrants: niche themes, emerging or declining themes, motor themes, and basic themes, as shown in Figure 1 in the appendix. "Design," "geometry," and "bio-inspired designs" are examples of basic themes that require further research and analysis before they can become motor themes. Figure 2 in the appendix shows the network visualization. Over the years, overlay visualization for co-occurrence analysis has shown an increasing trend in research examining the connection between biomimetic, kinetic, and adaptive facades. According to this, self-shading might be an emerging topic that needs more research.

3.2.3. Relevant Sources and Documents of Biomimetic and Self-Shading Publications

The most relevant source is "The Journal of Buildings," one of the top 10 sources as shown in Figure 3 (a, b) in the appendix, with 5 articles published [32, 43-46].

3.2.4. Most Cited Publications

Co-citation analysis was conducted to identify the most cited publications. As depicted in Figure 4 in the appendix, results were found for at least 80 citations. The largest group includes fourteen publications on biomimetic design for adaptive building façades, biomimetic principles, and bioinspired kinetic façade design [39, 47-49]. The top ten publications listed in Table 2 provide a comprehensive overview of the current literature. Some cover dynamic shading strategies, while others focus on designing adaptive facades for biomimetic and review studies. However, only a few publications are based on BSS studies.

Table 2.
Top-ten most-cited publications.

Ref.	Rank	Publication title	Authors	Journal	Citations	Total link strength	Year	Biomimetic	Self-shading
Hosseini, et al. [50]	1st	Bio-inspired interactive kinetic façade: Using dynamic transitory-sensitive areas to improve multiple occupants' visual comfort	Hosseini, et al. [50]	Frontiers of Architectural Research	135	44	2021	✓	
López, et al. [47]	2nd	How plants inspire façades. From plants to architecture: Biomimetic principles for the development of adaptive architectural envelopes	López, et al. [47]	Renewable and Sustainable Energy Rev.	118	238	2017	✓	✓
Hosseini, et al. [39]	3rd	A Morphological Approach for Kinetic Façade Design Process to Improve Visual and Thermal Comfort: Review	Hosseini, et al. [39]	Building and Environment	109	188	2019	✓	
Badarnah and Kadri [51]	4th	A methodology for the generation of biomimetic design concepts	Badarnah and Kadri [51]	Architectural Science Rev.	94	137	2015	✓	
Tabadkani, et al. [52]	5th	Design approaches and typologies of adaptive facades: A review	Tabadkani, et al. [52]	Automation in Construction	81	225	2021		✓
Al-Obaidi, et al. [13]	6th	Biomimetic building skins: An adaptive approach	Al-Obaidi, et al. [13]	Renewable and Sustainable Energy Rev.	78	375	2017	✓	
Badarnah [43]	7th	Form Follows Environment: Biomimetic Approaches to Building Envelope Design for Environmental Adaptation	Badarnah [43]	Buildings	65	330	2017	✓	
Xing, et al. [44]	8th	Exploring design principles of biological and living building envelopes: what can we learn from plant cell walls?	Xing, et al. [44]	Intelligent Buildings International	57	14	2018	✓	
Sheikh and Asghar [45]	9th	Adaptive biomimetic facades: Enhancing energy efficiency of highly glazed buildings	Sheikh and Asghar [45]	Frontiers of Architectural Research	40	92	2019	✓	
Kuru, et al. [46]	10th	Biomimetic adaptive building skins: Energy and environmental regulation in buildings	Kuru, et al. [46]	Energy and Buildings	37	282	2019	✓	

3.2.5. The Network of Prominent Countries

The results identified the 30 most prominent countries, with Italy at 40 publications and the UK at 35, as shown in Figure 5 (a,b) in the appendix. However, countries with arid desert climates should increase their contributions to such research.

3.2.6. The Network of Authors And Prominent Authors

The network of authors in Figure 6 of the appendix reveals that Badarnah L. is the top-cited author in each cluster, with 130 citations. She has the highest impact and H-Index among the top 25 authors, as indicated in Figures 7 and 8 (a,b) in the appendix. Her research significantly contributes to biomimetic environmental design in architecture. On the other hand, Figure 6 shows that the Journal of Buildings is the primary source, demonstrating the most significant connection with the keywords “biomimetics,” “building skin,” “architecture design,” “adaptive building envelopes,” and “kinetic facade.” It also highlights keywords such as "shading," “plant adaptation,” and “thermal comfort,” which are associated with some of the top authors. These themes are closely linked to the 20 most significant sources highlighted in the red cluster of Figure 9 in the appendix. However, there is limited focus on "shading,” with only three top authors researching this area.

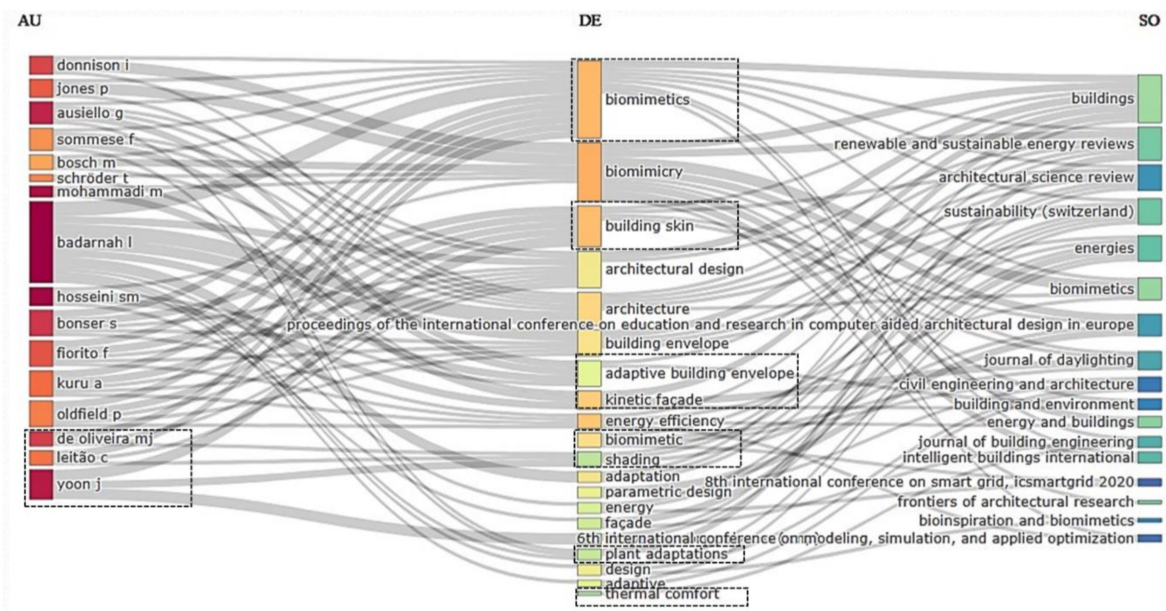
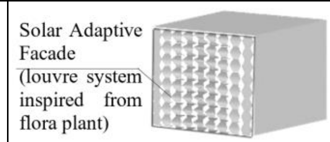
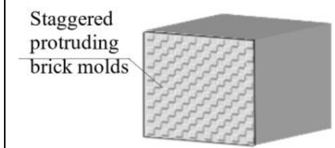
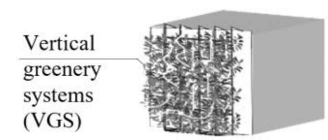
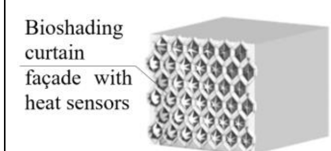
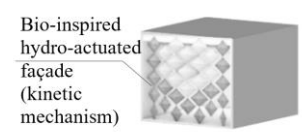


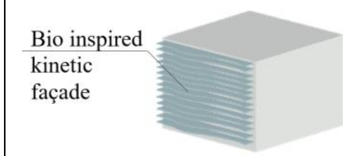
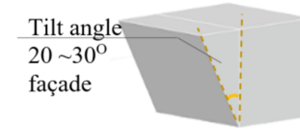
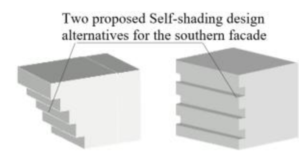
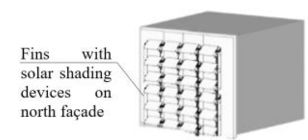
Figure 6.
The three-field plot correlates the top 20 keywords in the middle field, authors, and sources.
Source: Based on the biblioshiny tool.

3.2.7. Systematic Analysis of (Biomimetic and Self-Shading Technology)

This section delves into biomimetic and self-shading as depicted in the global scientific literature. It aims to pinpoint potential gaps in utilizing various shading techniques and biomimetic principles and to determine the degree of overlap between these two research domains. Most of the scrutinized studies have been conducted in arid desert climates, where solar exposure is the primary environmental factor under consideration. These studies predominantly propose designs for biomimetic, kinetic, and adaptive facades, with a limited focus on self-shading technology. Furthermore, a supplementary investigation was carried out by scouring the Google Scholar reference lists of selected publications to uncover any pertinent papers that might have eluded detection in the initial Scopus database search. Following a meticulous full-text screening, 28 publications were identified, detailed, and classified in Table 3.

Table 3.
Classification of selected articles according to these aspects: aim of study, climate, location, methodology, passive design (PD), active design (AD), self-shading (SS), kinetic façade (KF), biomimetic façade (BF), study plan, and extracted pattern/form.

Ref.	Aim study	Climate/ Location	Methodology	PD	AD	SS	KF	BF	Study plan	Extracted Pattern/form
Oliveira, et al. [53]	To explore the link between BIPV design traits and plant features adapting to varying solar radiation.	Mediterranean climate/ Darmstadt, Germany	Using an interdisciplinary approach to develop a framework for biomimetic adaptive solar building envelopes that integrate plant-inspired principles with photovoltaics.		✓		✓	✓	Simulation	
Shahda [31]	Propose shading for opaque walls to enhance thermal performance in buildings.	Hot and dry climate/ Egypt	Proposing alternatives for self-shading walls (inspired by termite habitats and cacti) by using bricks and evaluating them with simulation programs to achieve the best proposal that results in a temperature reduction for the surfaces.	✓		✓		✓	Simulation	
Su, et al. [54]	Review the research methods and metrics for evaluating VGS thermal effects.	Hot climate	Research on VGS thermal effects falls into two main categories: experimental and numerical studies.	✓		✓		✓	Simulation	
[53]	Develop a façade shading system for a pre-determined building and defined context, using Bioshading.	Hot and dry climate/ Lisbon	Assessing three key aspects of a new bio shading design method: (1) clarity; (2) experience sessions (PoC 1.0); and (3) operability and applicability.		✓		✓	✓	Simulation	
Sommese, et al. [55]	Define issues with hydro-actuated facades and establish principles for a	Hot and dry climates	This research presents a bio-inspired building facade based on a responsive plant, utilizing a 'bottom-up' approach.		✓		✓	✓	Simulation	

	responsive system that passively senses and actuates.										
Hosseini, et al. [50]	Propose an approach for integrating biomimicry principles of morphological adaptation with dynamic and human-in-loop systems for improving occupants' visual comfort	The annual climate/ Yazd, Iran	This research uses literature review, biomimicry, and parametric simulation to create a facade that enhances visual comfort.		✓		✓	✓		Simulation	
Lavafpour and Sharples [56]	Investigate the effectiveness of building geometry as an environmental design criterion	Hot climates/UK Passivhaus dwellings	The primary method employed in this study was computer simulation modeling as a substitute for direct measurement and experimentation.	✓		✓				Numerical & Simulation	
Capeluto [57]	The study assesses how the new building geometry affects energy performance compared to a traditional vertical facade.	Hot-semi arid climates/ Jerusalem	Performed analysis to assess the influence of solar radiation on the facade surface by testing various angles of tilting and orientations.	✓		✓				Simulation	
Alhuwayil, et al. [58]	Impact of climate and location on energy savings from passive shading and insulation.	Hot summer/ The northern hemisphere	The proposed shading strategy combines solar shading devices with self-shading techniques, utilizing high-performance materials and design principles to optimize energy efficiency and occupant comfort.	✓		✓				Simulation	

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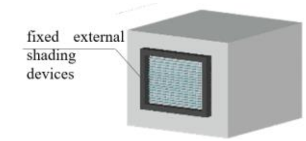
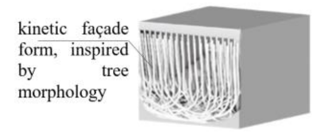
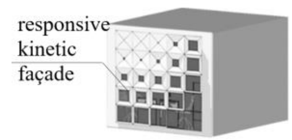
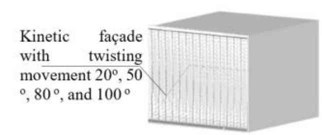
Koç and Kalfa [38]	Evaluating multiple parameters to identify energy-efficient external SD options for office buildings.	Hot summer Mediterranean climate/ Turkey's Antalya	The modeling step conducts dynamic energy simulations for annual heating, cooling, and lighting consumption across all scenarios (overhangs and louvers).	✓		✓			Simulation descriptive statistical analysis	
Hosseini, et al. [59]	Develop a multilayered biomimetic kinetic façade form to improve occupants' daylight performance.	Hot climates/ Iran/Deserts, Yazd	Observation, a biomimicry morphological approach (top-down), and parametric daylighting simulation.		✓		✓	✓	Simulation	
Hosseini, et al. [39]	Propose a kinetic façade that improves visual and thermal comfort by controlling solar and wind energy.	Hot-dry climate/ Iran	Six interconnected topics are explored: kinetic façade, biomimicry, building form, energy efficiency, comfort, and parametric design.		✓		✓	✓	Review & simulation analysis	
Sankaewthong, et al. [26]	Provide the vast solutions and probabilities of the façade forms being used to analyze the ability to provide sunlight in the environmental analysis.	The annual climate/ Thailand	This article explored kinetic façades to enhance indoor sunlight using a triple-identity DNA structure and a split into generation and evaluation.		✓		✓	✓	Simulation	
Nalcaci and Nalcaci [60]	Develop mechanical solutions for buildings to enhance their	all types of climate regions	Produce a new adaptive shielding form, including kinetic tubes for buildings through biomimesis by taking inspiration from the nature of energy and		✓		✓	✓	Simulation	

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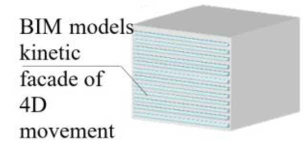
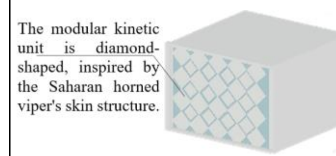
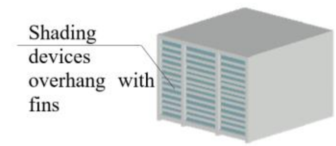
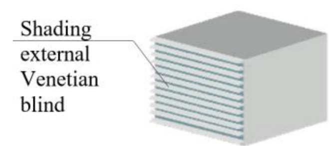
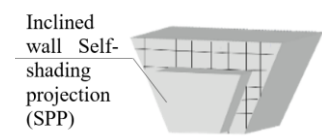
	environmental adaptability.		comfort problems.							
Hassan, et al. [61]	Develop a biomimicry-inspired building skin that can improve daylighting performance and promote visual comfort in office buildings in Assiut	Hot-dry climate in summer/ Assiut City, Egypt	The 'problem-based approach' applies the design principles extracted to the building skin design and evaluates the solution developed.		✓		✓	✓	Simulation	
De Luca, et al. [20]	Evaluate static shading devices to find the best option that enhances visual comfort, reduces glare, provides daylight, and offers views.	Hot, humid climate/ Tallinn	Measurements and calibration of interior surface materials through parametric modeling of the shading devices & creation of the daylight, spatial glare, view out, and energy models.	✓		✓			Simulation	
Huo, et al. [62]	Analyze and optimize the energy-saving performance of EVBS for NZEBs in different climates.	The annual climate/ China	The energy performance of EVBS for NZEBs is simulated and validated by field data, introducing a new indicator for evaluation.		✓		✓		Simulation	
Kandar, et al. [63]	Examine the effect of the inclined wall self-shading strategy on heat gain in an office building.	Hot, humid climate/ Putrajaya, Malaysia	The impact of inclined wall strategies on heat gain was studied through modeling and experiments on the inclined wall self-shading projection (SSP) using ApacheSim.	✓		✓			Simulation	

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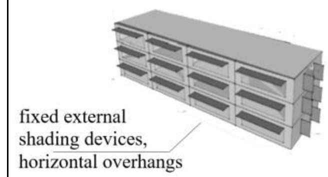
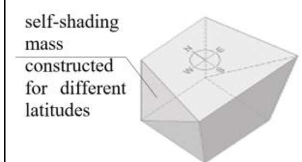
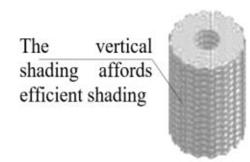
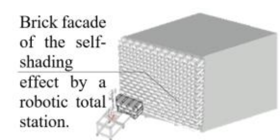
Gou, et al. [64]	Optimize the PD of newly built residential buildings in hot summer and cold winter regions of China for improving indoor thermal comfort.	Hot summer and cold winter / China , Shanghai	The base-case building model was designed with fixed external shading devices, consisting of horizontal overhangs on the south windows and vertical fins on the east and west windows.	✓		✓			Numerical	
Saifel nasr [65]	Proposing a simple tool to design a self-shading mass, resulting in an automatic seasonal adjustment.	Hot Deserts/ Egypt, Cairo	A design chart helps determine the depth of self-shading mass by adjusting the depth on one side and tilting a wall based on shading analysis.	✓		✓			Simulation	
Mohsenzadeh, et al. [66]	Examine how building shape affects energy consumption by managing excessive solar radiation in a tropical climate.	(Tropical rainforest)/ Malaysia	The study involved four basic geometries and simulated them in terms of their energy consumption.	✓		✓			Simulation	
Fleckenstein, et al. [67]	Investigate strategies to improve outdoor thermal comfort for pedestrians in cities with frequent extreme heat events.	Warm summers and cold winters/ City of Munich	Researched self-shading brick facades, designed tools for site-specific solutions using microclimate simulation, developed a robotic construction workflow, and validated methods with a 1:1 scale object.	✓		✓			Simulation	
Zupan, et al. [68]	Explore the potential of a morphing cactus tile that has a dynamically	Semi-arid desert climate/ Phoenix, Arizona	A generally applicable algorithm was utilized and is presented to quantify the area of an arbitrarily shaped/oriented surface that is in shade for any		✓		✓		Numerical	

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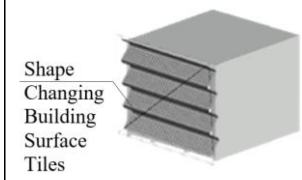
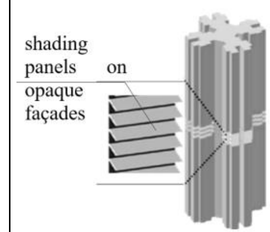
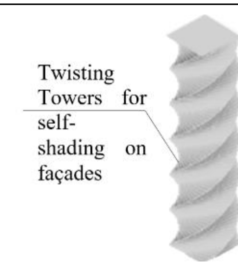
	changing wrinkle pattern, which could control the level of self-shading provided by the façade based on the time of season.		given date/time and geographic location.							
Liu, et al. [19]	Proposes the adoption of shading devices on opaque façades and evaluates their energy-saving potentials under near-extreme summer conditions by conducting building energy simulations.	Hot and humid summers/ Hong Kong	This study evaluates OTTV with and without self-shading, factoring in the shading coefficient (SC) and WWR for thermal performance.		✓		✓		Simulation	
Jakica and Kragh [69]	Evaluate the self-shading advantages of twisted geometries by correlating floor-to-floor rotation with façade solar exposure in hot climates, where it can serve as a passive solar strategy.	Varies Climate/ USA	The calculation of solar irradiation involves twisting a rectangular floor shape before performing the calculation.	✓		✓			Simulation	
Nikpour, et al.	Examining building envelope energy	Hot and humid climate/ Malaysia	This study evaluates OTTV with and without self-shading, factoring in the shading	✓		✓			Simulation	

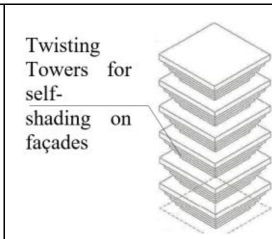
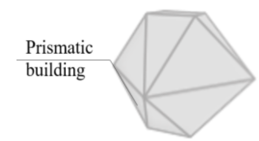
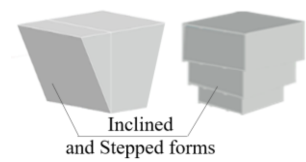
[70]	performance via (OTTV) and quantifying OTTV reduction to demonstrate how self-shading strategies lower energy use.		coefficient (SC) and WWR for thermal performance.								
Adinugroho and Gadi [71]	Investigate diverse, innovative prismatic forms for their thermal performance by analyzing the outside heat balance.	Hot arid desert climate/ Sao luis, Cario and el Helsinki	Modelling eight examples of prismatic forms and exploring the possibility of establishing an indicator that can be used to characterize prismatic forms.	✓		✓				Simulation	
Freewan [72]	Explore the potential of building forms to improve energy performance and interactions with sun rays.	Hot, arid climate/ Jordan	Investigate how building shapes affect energy efficiency and sunlight metrics such as isolation and heating/cooling loads, which were assessed using IESVE SunCast, EnergyPlus with DesignBuilder.	✓		✓				Simulation	

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Table 3 illustrates that research on self-shading (passive design) and biomimetic approaches has a lower proportion than studies on biomimetic and kinetic facades (active design). Most studies have examined the impact of hot climates in various countries. The most commonly used strategies are sloped and stepped surfaces, which, when oriented in a specific direction, allow for a significant reduction in heat gain compared to the baseline. Depending on the orientation, this strategy reduced the cooling load by more than 10% compared to the baseline. Furthermore, tilted walls and folded façade strategies seem to have a promising impact in reducing solar radiation and increasing daylight performance by more than 30%, but there could also be a potential increase in heating load. It has been observed that a certain degree of cooling load reduction during the northern tilt of the façade did not make any noticeable difference.

Regarding energy modeling methods, the surface temperature measured by Shahda [31] was of the bricks overlain by the protruding portion. While energy modeling resulted in a reduction in surface temperature, the study did not consider the protruding brick surface itself, which may negatively contribute to the overall heat transfer of the brick wall. Furthermore, the relationship between energy performance and the combination of geometric, material, and computational tools has not been effectively explored due to the limitations of simulation tools and the relative novelty of dynamic techniques. Most studies on self-shading focus on building form rather than façade components, offering a more practical approach than larger-scale interventions. Many studies use a combination of opaque and transparent surfaces, but few studies pertain solely to shading opaque surfaces.

As for the materials, self-shading is often examined using a combination of glazed and non-glazed materials, as explained by Alhuwayil, et al. [73]. This makes it difficult to determine whether the results are primarily due to the glazed or non-glazed elements. Therefore, further studies should aim to analyze individual elements to determine their self-shading effects. The study by Mohsenzadeh, et al. [66] reveals that among the four basic floor plan shapes considered, the triangular building receives the highest percentage (approximately 60%) of total solar radiation, followed by the square and rectangular shapes with approximately 59%, and the circular shape with approximately 57%.

Based on the analysis of these studies, self-shading can be a practical passive strategy, especially in hot and dry climates. This effect can be understood through the biomimetic concept of cactus ribs and Australian leaf palms, which provide shaded surfaces that lose heat through their ribs. Additionally, the termite, widespread in hot regions and temperate highland forests, efficiently applies the principle of self-shading in forming its habitat from the outside. The termite colony appears as branched towers reaching heights of up to four meters (see Figure 7). The mass of the termite mound is characterized by its prominent pillars, which increase the surface area of its outer surfaces and support its stability. These supports help create shade on the surface and facilitate the cooling process through air movement on the outer surface of the settlement [74] as shown in Figure 7.

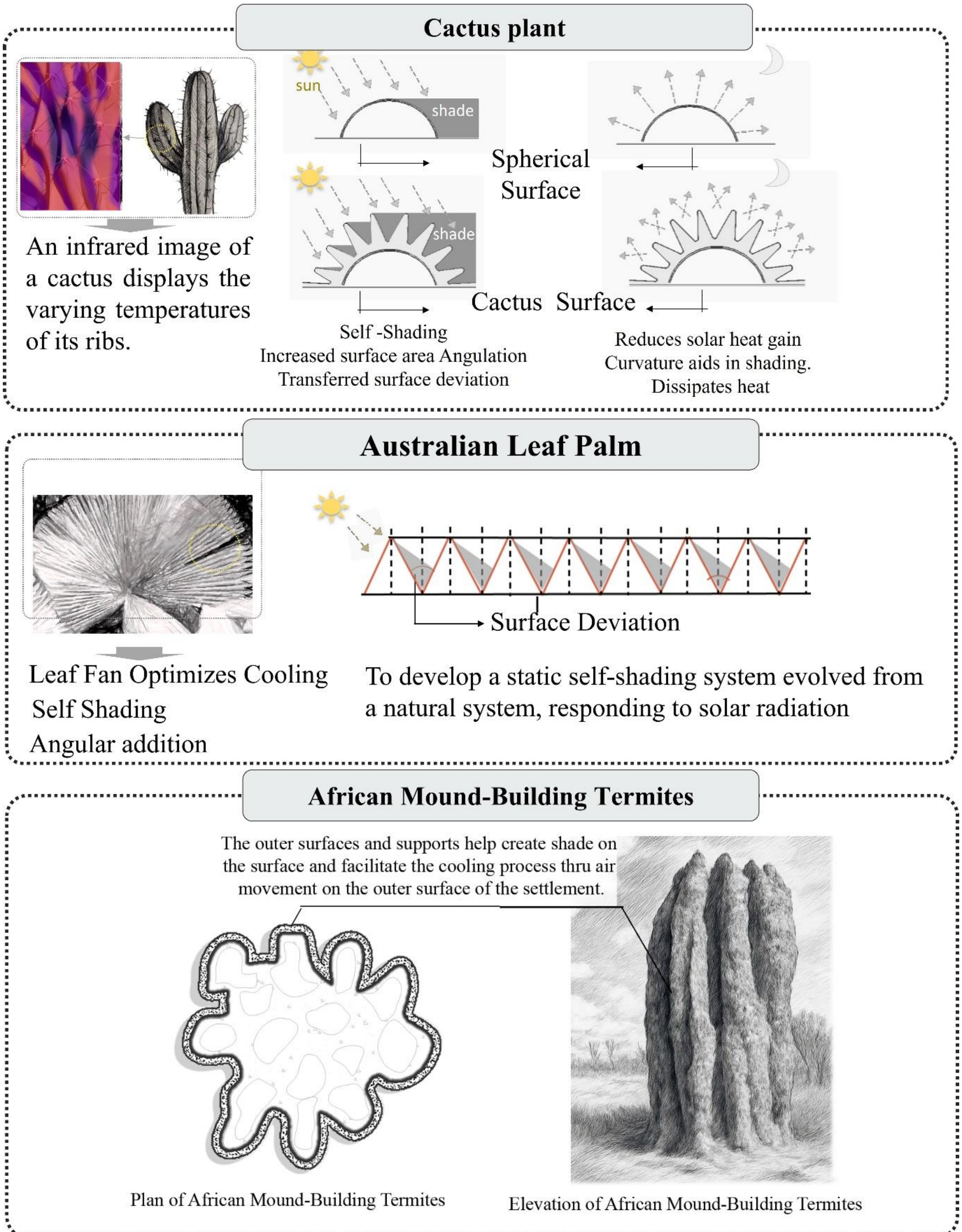
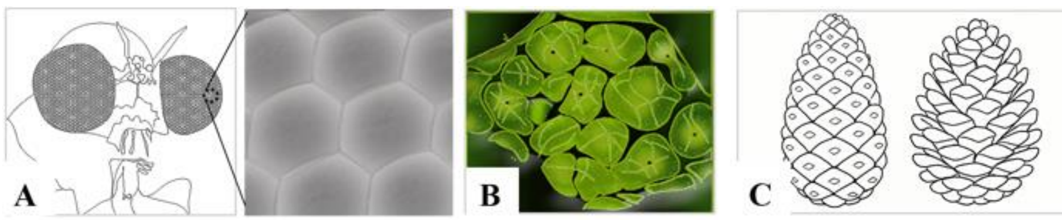


Figure 7.
Natural system Analysis to develop a static self-shading.
Source: The authors based on Shahda [31], Fagundes et al. [75], and Roth-Nebelsick and Krause [75].

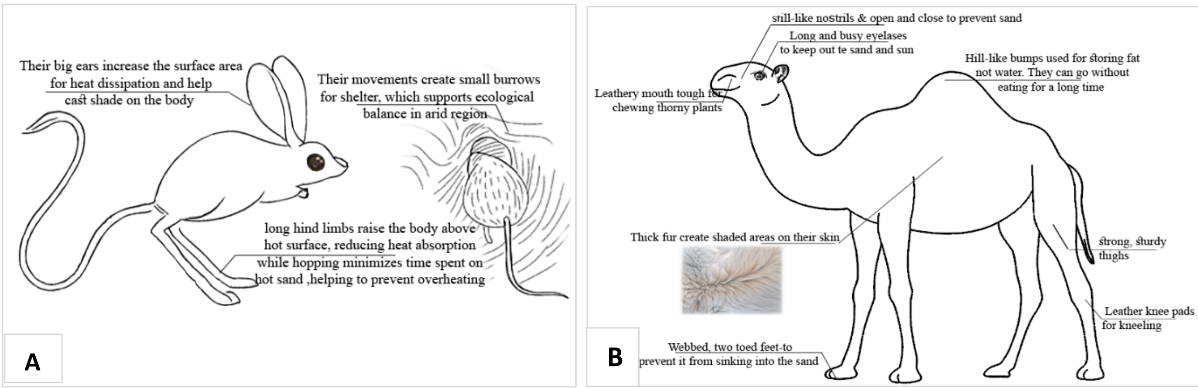
3.2.7.1. Environmental Adaptation in Nature (Self-Shading at the Cellular Level)

Living organisms and their environments are interconnected. They have evolved through various adaptation strategies to survive different environmental conditions. Harsh factors, such as temperature, humidity, solar radiation, and extreme pressure, create significant survival challenges for these organisms. Adaptation in organisms occurs through various means: some utilize skin adaptations like fur, while others rely on built structures such as mounds [76]. The following Table 4 classifies morphological and behavioral adaptations, which complement physiological self-shading strategies in desert organisms.

Table 4.
Classification of morphological and behavioral adaptations that complement physiological self-shading strategies in desert organisms.

1. Physiological adaptation	An organism's reaction to an outside stimulus to preserve homeostasis is known as physiological adaptation. For example, the geometrical arrangement of ommatidia in insect eyes allows for self-shading, regulating light exposure, and improving visual function, see fig. A. Similarly, plant chloroplasts under high light move within cells to produce self-shading, minimizing photodamage and maximizing photosynthetic efficiency, see fig. B. Also, pine cones open and close in response to the sun's heat to protect and disperse seeds, see fig. C 
2. Behavioral adaptation	Behavioral adaptations help organisms survive by allowing them to respond to environmental changes. For instance, lizards and desert rodents often become nocturnal or crepuscular (active during dawn and dusk) to avoid daytime heat and intense sunlight, see fig. A. Similarly, ants and other small insects regulate their exposure by retreating to shaded nests or burrows when the sun becomes too intense, see fig. B. Also, some plants cast shade over their leaves to reduce direct sunlight during the warmest times of the day, a behavior known as solar tracking or heliotropism, see fig. C. 

3. Morphological adaptation	Morphological adaptations are structural features that improve survival in specific environments, such as size, shape, and pattern. Color is an important factor in reducing heat absorption, so lighter skin is more common in animals living in the desert. For example, the jerboa makes holes to hide from the sun's rays, thereby minimizing the effects of solar radiation, see fig. B. Also, camels, their thick coats and long limbs shade parts of their skin, keeping them from being too hot, see fig. B.



Source: The authors based on Ismail, et al. [9], Hosseini et al. [39], [72], Zhang, et al. [77], Rupp and Gruber [78], Ruberti, et al. [74], Ioannou and Laskowski [79], Eggermont, et al. [80] and Chan [81].

This research direction may offer new insights into the application of self-shading at the level of building facade components. However, only a limited number of studies explore this possibility, and there appears to be ample scope for further investigation.

While many studies focus on building geometries, fewer have explored the possibility of self-shading through façade components, as shown in Table 5.

Table 5.
A synthesis of previous studies on self-shading, covering aspects such as climate, design methods, biomimetic levels, self-shading technology, evaluation metrics, utilized programs, and improvement of environmental performance.

Ref:	Climate / location	Design method	The function	Biomimetic Level	Self-Shading technology	Environmental Performance Indicators	Program used	Improvement of environmental performance (%)
El Ahmar and Fioravanti [82]	Hot climate/ Egypt	Shading system inspired by the form of folding in leaves and cacti.	Office room	Organism Level	Façade Component (horizontal and vertical folded surface)	Annual insolation Daylight Autonomy Over-lit areas Annual cooling loads	Grasshopper plugin, Rhino 3D modeller, and DIVA plugin	Minimize cooling loads without sacrificing daylight needs.
Sadegh, et al. [11]	Hot-summer Mediterranean climate	The shading system is inspired by the form of the Lotus flower and the movement of the human body muscles.	Office building	Organism Level, Behavior Level	Façade Component (Dynamic Façade Movement)	(UDI), (SDA), (ASE), and the perceptibility of glare	Rhino, Grasshopper, and Diva.	SDA: 62.9% annual cooling load reduced: 74% annual isolation reduced: 22%
Hosseini, et al. [59]	(Hot Deserts, Yazd) climates/ Iran	Shading system inspired by stomata distribution and movement. With Complex biomimetic skin.	Small-scale indoor garden	Organism Level, Behavior Level	Façade Component (Glazing with perforated shading) Forming a façade shape from a tree morphology	(UDI, sDA and DGP) daylight glare probability	Rhino 6, Grasshopper, and Diva simulation	Performance of metrix UDI (83.5–85.5%) SDA(49.4–50.6 %) DGP(0.31–0.4)
Mohamed Abd El-Rahman, et al. [83]	Hot climate	Shading system inspired by the shape of a mangrove flower, a cactus, and the whirling motion of a white moonflower.	Biomimetic envelope	Organism Level, Behavior Level	Building Geometry (Dynamic Façade Movement)	Reduce Energy Consumption Glare	"Grasshopper" in Rhino, ladybug & Honeybee plugins	Reduction of heat gain, & The comfort hours increased by 2873 hours per year
Shahda [31]	Hot and dry climate	Shading system inspired by habitats of termite settlements and the cactus surfaces.	Geometric patterns	Organism Level, Behavior Level	Façade Component (Brick configuration)	Surface Temperature and heat radiation gain	Design Builder Program	heat radiation gain South: 44.68–63.83 % East: 5.39 % West: 42.86–82.57 %
Capeluto [57]	(Hot-semi arid, Jerusalem)	Performed analysis to assess the influence of solar radiation on the facade surface by testing various angles of tilting and orientations. Using Solar Collection Envelope (SCE).	Office space	—	Building Geometry (Tilting form with partially glazed) Inverted pyramid building	Solar radiation gain & Energy consumption	computer model SustArc ENERGY simulation	Solar radiation gain: East: 25–75 % West: 8.33–50 % South: 8.33–100 %

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Kandar, et al. [84]	Malaysia (Tropical rainforest)	Reductions of heat transfer into the Diamond building due to its incline A wall facade that provides self-shading on the building.	Commercial building	—	Building Geometry (Tilted glazed wall Façades)	Illuminance (DF) Relative Humidity	HD35-data logger Lux meter sensor	Illuminance in the building resulting from daylighting alone is above 200 Lux. Average daylight factor is 2.7%
Mohsenzadeh, et al. [66]	Malaysia (Tropical rainforest)	The study involved four basic geometries and simulated them in terms of their energy consumption.	Commercial Penang Building, Malaysia	—	Building Geometry	DF Energy consumption Solar gain Cooling load PMV	Design Builder simulation	Solar Gains Exterior Windows kWh, 17272,41, 59% Cooling (Electricity) kWh, 8682,204, 30%
Fleckenstein, et al. [67]	oceanic climate / City of Munich	Researched self-shading brick facades, designed a tool for site-specific solutions using microclimate simulation, developed a robotic construction workflow, and validated methods with a 1:1 scale object.	Brick wall size of 3m by 2m	—	Building Geometry (Urban barrier for pedestrians (Brick configuration)	Solar radiation, optimal self-shading effects and Surface temperature	Rhino, Grasshopper simulation, thermal camera, and EnergyPlus	The average surface temperature of a brick showed a maximum decrease in surface temperature of 4.7°C between the self-shading geometry at the right part and the flat geometry on the left part of the wall
Alhuwayil, et al. [73]	Hot deserts, Dhahran/ Saudi Arabia	Analyzing the assembly of shading fins and louvers across various types and sizes.	Multi story hotel building	—	Façade Component Overhang, fins and louvres	Heating, Cooling Load Cost	Design Builder simulation	Heating: 0.85–20.51 % Cooling Load: 5.57–20.51 %
Chan and Chow [85]	Hot summer/ China and Hong Kong	Determining self-shading modified the inclined wall angle while also automatically increasing the roof area	Office building	—	Building Geometry (Inclined walls)	Cooling load Heating load Diffuse radiation	EnergyPlus	Cooling load, 0.64 % - 10.19 %, Heating load 125 % to - 700 % Diffuse radiation North: –33.33 to - 8.33 %, South: –33.33 to 16.67 %, East: –33.33 % to - 8.33 %, West: 10 % - 40 %
Atthaillah, et al. [86]	Tropical climate/ Indonesia	Possible schemes were evaluated by adjusting the window-to-wall ratio and wall slope length.	School buildings	—	Building Geometry	Illuminance (UDI) (sDA) (ASE) (DGP)	Illuminance meter Rhino, Grasshopper And the Octopus simulation	UDI: 32.37–445.68 % DGP:41.94 %

Su, et al. [54]	Hot summer	A systematic review of mechanisms behind the thermal effect of vertical greenery systems.	---	Behavior Level	Façade Component & Green façade	Overall thermal impact of (VGS) air temperature, surface temperature heat flux thermal comfort	EnergyPlus ENVI- met simulation CFD	——
Lavafpour and Sharples [56]	Moderate temperatures and high humidity. / UK	Weather data is used for simulation to assess overheating risk. The façade geometry is optimized for energy efficiency and evaluated against current and future weather for long-term performance.	Passivhaus dwellings	—	Building Geometry (Tilted walls)	Indoor operative temperature DF Heating demand Cooling demand	Design Builder simulation	Winter: 6.67 % - 13.33 % Summer: 3.33 % -6.67 % DF10 :–40 % Heating demand: - 11.11% to -111.11 % Cooling demand 100 :%
Alhuwayil, et al. [58]	Hot summer /the northern hemisphere	The shading strategy integrates solar shading devices and self-shading. Alternatively, using high-performance insulation and glazing in the building envelope can negate the need for solar shading.	Multistory hotel building	—	Façade Component (Fins, Overhang, and Louvers)	Cooling degree and heating energy demands, global horizontal irradiance, and solar shading effectiveness.	Design Builder	Passive solar shading saved up to 65.2% in Khamis Mushait and at least 13.1% in Athens. High-performance insulation varied from -11.6% in Khamis Mushait to 8.5% in Athens, linked to their 2% and 48% heating demands.
Koç and Kalfa [38]	Hot summer Mediterranean climate/ Turkey's Antalya	The modeling step then involves performing dynamic energy simulations and calculating annual heating, cooling, and lighting energy consumption values for all scenarios.	Office building	——	Façade Components (Shading, Overhang, horizontal louver, Vertical louver)	heating (H), cooling (C), lighting (L), and total energy consumption values (W/m2)	Design Builder BM	Total energy saving (%):70%
De Luca, et al. [20]	Humid continental climate / Tallinn	Measurements and calibration of interior surface materials through parametric modeling of shading devices & creation of daylight, spatial glare, view out, and energy models.	Classrooms in the northern city of Tallinn	——	Façade Components (Different overhangs, louvers, fins, and panels	(DF), (cDA) and (UDI)	Rhino, Grasshopper, and Energy plus	Static shadings cut visual discomfort by 89.8%, saved up to 29.1% in energy, and provided ample daylight and views. cDA efficiency rose by 28% in New York, 15% in Anchorage, and 44% in Phoenix, with electric light savings of 22% to 35%.

Kandar, et al. [63]	Hot, humid climate/ Putrajaya, Malaysia	We used ApacheSim to model and test inclined wall shading to study its effect on heat gain.	Office building	--	Building Geometry inclined wall self-shading)	Ambient temperature, relative humidity, dew point, and wet bulb temperature	ApacheSim simulation software	The optimum inclination angle of self-shading for effective heat gain reduction is based on a 45% self-shading projection
Gou, et al. [64]	Hot summer and cold winter /China , Shanghai	The base-case building model was designed with fixed external shading devices, consisting of horizontal overhangs on the south windows and vertical fins on the east and west windows.	Residential buildings	—	Façade Components	(CTR) and (BED)	EnergyPlus	The annual indoor thermal comfort hours are extended by about 516.8–560.6 h, and the annual building energy demand is reduced by about 27.86–33.29%
Mahdavinejad, et al. [87]	Cold semi-arid: Tehran, Ardabil - Hot semi-arid: Bandar Abbas - Moist mild-latitude: Rasht	Self-shading by an inclined wall effectively controls energy consumption and glare in Tehran's semi-arid climate.	Office building	___	Building Geometry (rotating façade wall)	energy efficiency and occupants' visual comfort: Quality of view (QV), (UDI), and energy use intensity (EUI)	Grasshopper and Rhino software &Radiance, Daysim, and EnergyPlus calculation engines	This research stated that using a self-shading design could increase the quality of view by up to 75% while reducing energy consumption and the risk of glare & the rotating façade wall reduced cooling energy demand and intensity by 10°-30° in select models.
Saifelnasr [65]	Hot Desert climate, Cairo / Egypt	A design chart helps set the self-shading mass depth, adjusted with a tilted wall for effective shading.	Royal Ontario Museum	—	Building Geometry (Tilted wall)	Solar heat gain	Utilizing a design chart	The author made a design chart for a self-shading building that shades fully in summer and lets in solar heat in winter, but didn't specify exact amounts.
Jakica and Kragh [69]	(Varies climate)/ USA	The calculation of solar irradiation involves twisting a rectangular floor shape before performing the calculation.	Twisting Towers	___	Building Geometry (Twisting tower)	Solar irradiation (harmful)	Rhino + Grasshopper simulation	-43.5% to 28.8% (greater twisting angle increases harmful solar irradiation), with a reduction of up to 70 kWh in hot climates.
Nikpour, et al. [70]	(Tropical Rainforest climate)/ Malaysia	This study assesses (OOTV) and compares (OTTV) with and without self-shading, considering the shading coefficient (SC) and window-to-wall ratio (WWR) for thermal performance evaluation.	High-rise building	—	Façade Components (Finding the optimum size of the window for controlling the OTTV).	(OTTV)	OTTV manual calculation	The self-shading strategy in high-rise buildings effectively reduces the OTTV by 68.94 times the Window-to-Wall Ratio, as demonstrated in Malaysia.

Bhai, et al. [88]	(Hot Desert climate) Cairo Egypt	The glass windows were angled to comply with building code requirements, followed by further analysis.	Office Space	—	Building Geometry (Tilted glazed wall Façades)	(sDA)	Rhino & Grasshopper simulation	The performance of sDA: North: 63.02 % South: 57.55 % East: 75.28 % West: 79.17 %
El Ahmar and Fioravanti [89]	(Hot Desert climate) Cairo Egypt	The biomimetic concept used folding strategies to design a double-skin façade shading screen for an office.	Office Buildings	The termite mound behavior in natural ventilation	Building Geometry (Folded façade)	Cavity temperature Air change per hour Cooling load	Rhino, Octopus plugin & simulations in Energy Plus, and DIVA for daylight simulations	Cavity temperature 3.23–4.84 % Cooling load: South East: 5.08 % North West: 10.03 %
Maderspacher and Moosberger [90]	Spain (Hot-summer Mediterranean, Madrid)	The shading device's variable solar transmittance and heat gain require an updated double façade model with an air gap for accurate heat transfer.	Building house	——	Building Geometry (Zigzag self-shading Pattern)	IDA-ICE (Indoor Climate and Energy Simulation Program	Indoor temperature Solar radiation	Improvement of Indoor temperature 13.21 % & Solar radiation 34.29–57.14 %

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Based on the previous analysis, the self-shading strategy in most studies relies more on building geometry than facade components. Additionally, the prevailing climate in the studies is hot and dry. Stepped or sloped wall designs are used in the majority of studies. Biomimetic design has been employed at the organism or behavioral level, primarily in kinetic facades. The software most frequently used to evaluate environmental performance indicators such as surface temperature, thermal radiation gain, UDI, SDA, and ASE included Energy Plus, Rhino, Grasshopper, and Diva. In contrast, other indicators were less commonly evaluated. Implementing a self-design strategy can improve these environmental performance indicators.

4. Discussion

Energy and climate change challenges in hot and dry climates have driven researchers to develop self-shading designs inspired by nature, highlighting the importance of biomimetic self-shading. Based on the significance of passive design strategies in such challenges, a literature review has also demonstrated various approaches to developing and evaluating self-shading buildings. A review of the Scopus database shows a significant increase in publications on this topic in recent years. In contrast to kinetic and adaptive facades, analysis indicates that the relationship between self-shading and biomimicry is an emerging topic worth exploring. Although some strategies, such as research [31], have proven successful, there are still significant gaps in the comprehensive analysis of specific aspects. Future research initiatives will aim to address these gaps. This section discusses the biomimetic morphological approach to self-shading, environmental performance indicators, opportunities and challenges, and a proposed design strategy for BSS buildings.

4.1. Biomimetic Morphological Approach to Self-Shading

Morphology is a scientific approach that investigates shape, form, and pattern. It can be evaluated in the built environment at the architectural level by examining building shapes and envelope types Bhai, et al. [88], Oliveira [92], and Qu and Kang [91]. Naili, et al. [92] examined various façade morphologies, classifying them according to shape (e.g., folded) and transparency (e.g., opaque or shaded) to identify the most efficient model for lowering energy consumption. Therefore, this review investigates self-shading using a classification system based on a morphological approach, which includes two distinct types: self-shading by façade components and overall building form. Regarding façade components, several studies have explored self-shading facades created through sets of horizontal, vertical, and mixed ribs that increase shaded areas, as shown in Figure 8 (A, B, C). These studies show that shaded brick areas can significantly lower surface temperatures [31, 54, 67, 78].

Furthermore, Fleckenstein, et al. [67] compared the performance of protruded and perforated bricks in wet and dry conditions. Their analysis concluded that protruded bricks outperform perforated ones, leading to an average decrease of 3.1°C in surface temperature. Conversely, perforated bricks perform poorly due to greater sunlight exposure. Also, Shahda [31] drew inspiration from cactus ribs and utilized them as self-shading elements, experimenting with different rib orientations such as horizontal, vertical, and mixed designs. The study revealed that horizontal ribs have the most significant impact on reducing external surface temperature, followed by vertical and mixed ribs.

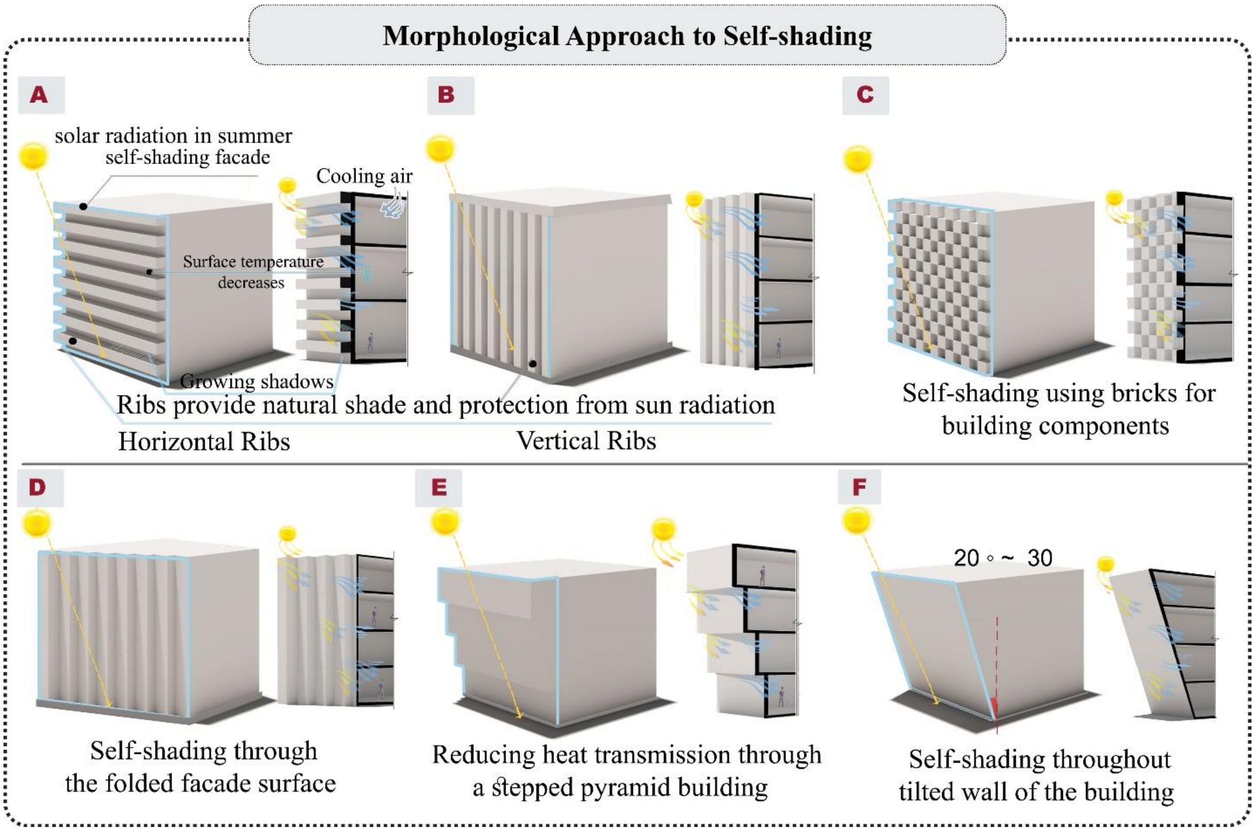

Figure 8.
Morphological Approach to Self-shading in two distinct forms: self-shading building form and self-shading façade components.
Source: The authors based on Shahda [31], López, et al. [47], Su et al. [54], and Alhuwayil, et al. [58].

These observations in Egypt consider self-shading effects from the south, west, and east orientations. Horizontal ribs show an average surface temperature difference exceeding 13°C compared to the base case in all orientations. Rupp and Gruber [78] conducted a nature-inspired study focusing on self-shading forms mimicking leaf protrusions to enhance heat transfer. They suggest protrusion shapes, patterns, and environmental variables influence heat transfer efficiency through evaporation. Self-shading facade components utilize various design strategies, including irregular shapes like folded facades and stepped pyramids (the graded facade), as shown in Figure 8 (D, E).

For instance, El Ahmar and Fioravanti [89] created an innovative system inspired by the habitats of termite settlements. Their approach integrates insulated aluminum panels with strategic cavity ventilation, demonstrating that folding and varying cavity depths can significantly enhance convective heat loss. Similarly, Hosseini et al. [59] drew inspiration from plant branches to create forms that significantly reduce daylight glare probability. An innovative approach by Yoon [95] involved kinetic folding, using a bi-layer polymer sheet that expands in response to solar radiation, effectively preventing overheating in its folded state. Furthermore, Mohamed Abd El-Rahman, et al. [83] investigated how folding patterns affect self-shading and solar radiation on building facades. Furthermore, morphing curving shapes were used to enhance the covered area of the facade while reducing solar irradiation[19, 65, 68, 71, 93].

The primary focus in the literature on self-shading was the shape of the building. The discussed studies suggest modifying the building geometry to achieve self-shading and minimize solar radiation on the façade, thereby reducing surface temperatures [94]. For example, Jakica and Kragh [69] explore building form by twisting a rectangular plane to alter the surface exposure to solar radiation, resulting in an average irradiance reduction of 70 kWh/m². Additionally, as shown in Figure 8 (F), using an inverted pyramid or tilting form is prevalent in studies where upper floors shade the lower ones [58, 65]. A prevalent method to mimic the inverted pyramid effect on a smaller scale is tilted walls [72, 84]. Tilting building envelopes, such as walls, to block direct solar radiation, especially in summer, can reduce energy consumption in HVAC systems [56, 86, 88]. Studies indicate that wider tilting angles can decrease cooling loads but may increase heating loads. Larger angles can also enhance diffuse radiation from ground reflection. Chan and Chow [85] compared two identical buildings regarding location, number of openings, and materials. They found that self-shading is effective at vertical tilting angles of 20 to 30 degrees, as depicted in Figure 8 (E, F).

Mild wall tilting across the building envelope has shown positive results; for instance, Zerefos, et al. [95] found that modifying one building's exterior wall led to a similar improvement in energy consumption (with ± 0.7% area and ± 0.2% volume compared to the base scenario). For instance, the building with the inclined wall experienced 37% less sun radiation during the cooling time. Previous research indicates that tilting facades can reduce cooling loads in smaller structures, such as one-story buildings. Overall, triangular and rectangular forms dominate self-shading research in facade components, but it is clear that a wide range of unique designs and natural inspirations are being investigated to improve the performance of self-shading technology.

4.2. Environmental Performance Improvement Indicators

Previous research in Table 3 focuses on improving the performance of self-shading buildings in hot climates using a variety of indicators, including daylight, OTTV, airflow, surface temperature, air temperature, solar radiation gain, energy consumption, thermal comfort, heating/cooling load, and sunlit hours per area [67]. Most research has evaluated solar radiation gain and energy consumption, influenced by indoor-outdoor temperature differential (ΔT), sun temperature, and surface temperature. Lavafpour and Sharples [56] and Shahda [31] found that increasing the slope of the outer facade of the western wall by 20 to 30 degrees reduced radiation by 50 watts per square meter [90]. The heat transmission through walls, represented as "φ," is controlled by various factors, including the U value (heat transfer rate), wall area (A), and the temperature difference (ΔT = T1 - T2) across the wall. The following equation expresses thermal transmittance: $\varphi = A \times U \times (T1 - T2)$. To reduce φ, employ materials with a low U value or lower the surface temperature, as shown in Figure 9. Shading the external surface decreases ΔT and reduces heat transfer to the building [31].

According to the study by Adinugroho and Gadi [71], a decrease in average annual solar radiation does not automatically lead to an increase in heating load. The prismatic building model collects more solar energy in the winter, despite lower levels in the summer. The surface temperature also affects solar radiation [31, 67, 96]. In Shahda [31], walls with projecting bricks reduced surface temperature [67, 88], whereas self-shading was evaluated based on the self-shaded area of the facade. Fleckenstein et al. [67] investigated the influence of self-shading bricks through simulation and robotics. Oliveira et al. [53] discovered that the ribbed surface of barrel cactus has a total convective heat loss of 2.5 times that of the flat surfaces and a 44% higher convection coefficient compared to a flat surface. Similarly, Hosseini et al. [59] and Saifelnasr [65] investigated self-shading using biomimetic plant morphology and the DIVA software for Rhinoceros to measure solar radiation.

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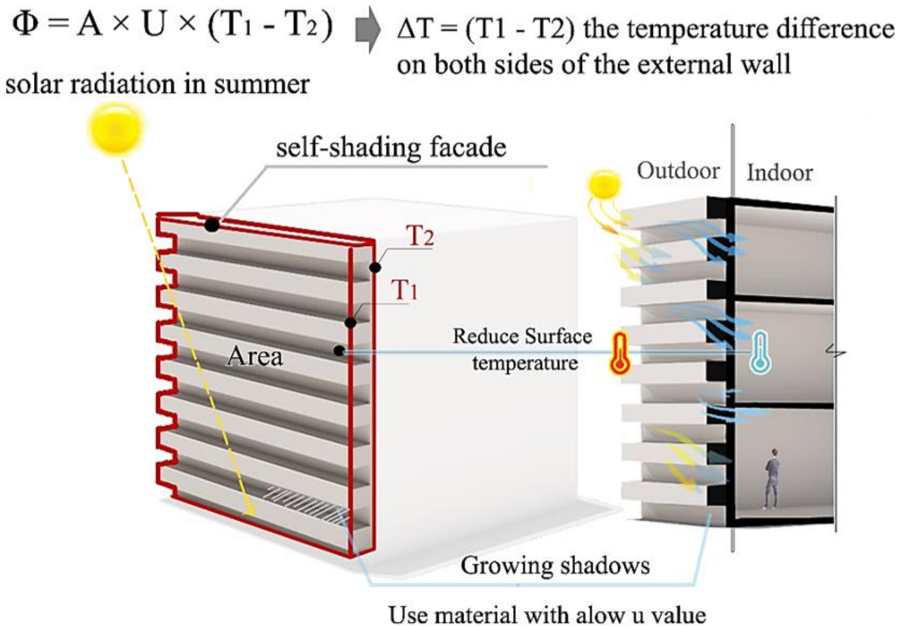


Figure 9.
Calculation of the amount of heat transferred through the walls (φ).
Source: The authors based on Shahda [31] and Roth-Nebelsick and Krause [75].

Daylight is an important indicator of environmental performance. It can be quantified through various metrics, such as daylight factor (DF), illuminance, daylight autonomy (DA), exposure hours, and useful daylight illuminance. Bhai, et al. [88] examined daylight performance by tilting facades 20 degrees while balancing (sDA) and (ASE). Self-shading can improve natural daylight and reduce dependency on artificial lighting in workspaces. Mohsenzadeh, et al. [66] used (DF) as a performance parameter, stating that a (DF) value of around 2% indicates successful self-shading for maximum daylight consumption. As for self-shading facades, key design improvement indicators are orientation, shading length, (WWR), and automatic daylight dimmers. A 2.5 m self-shading extension can maximize energy savings in the 20% to 100% WWR range. The best orientation for self-shading is east, while north is less suited. Optimized daylight dimmers can reduce energy consumption by up to 12%. Compared to other shading systems, self-shading at a WWR of 20%-80% is the most efficient, saving the most energy for numerous orientations. (PET), (PMV), and (PPD) are measures used to quantify indoor thermal and visual comfort [97].

The index for improving thermal and visual comfort relies on metrics such as the PET, the PMV, and the PPD to assess thermal sensation in indoor environments. These metrics take into account factors such as air velocity, temperature, and humidity to ensure an accurate assessment of thermal comfort. When assessing thermal comfort indicators, it is critical to examine the physical components, the human factor, and thermal comfort measurements, including PMV and PET. Key considerations for assessing visual comfort include light intensity, homogeneity, color rendering quality, and occupant glare risk prediction [98]. As for the software used in evaluating and simulating self-shading, EnergyPlus is considered the most common, as it is used in tools like DesignBuilder and Rhino to assess solar heat gain and surface temperature.

4.3. Opportunities of BSS in Buildings

Utilizing BSS technology at both the facade and building levels presents various opportunities for self-shading as follows:

- Self-shading has a significant impact on energy consumption in buildings, especially during the summer, as it reduces cooling requirements to control indoor temperatures [73, 95].
- Using BSS, which simulates how some types of plants protect themselves from direct sunlight, Shahda [31] architects can reduce glare without sacrificing natural light [38, 99, 100].
- The study by Shahda [31] confirmed the environmental benefits of a brick façade due to its self-shading capabilities, indicating that it may have a greater impact than adding more insulation throughout the building's life cycle.
- BSS enhances lighting conditions in buildings by effectively balancing heat reduction and access to natural daylight. These systems can achieve a (DF) of nearly 2%, demonstrating their efficiency in self-shading and daylighting [101].
- BSS has the potential to increase a building's overall sustainability, in addition to its ability to improve thermal, visual comfort, and daylighting performance [102].
- Self-shading of façade surfaces can reduce thermal stress for pedestrians by modifying the local climate [67].
- Finally, self-shading reduces solar heat gain, lowering cooling needs and energy use, which supports the construction industry's transition to sustainability [73, 85, 95, 103].

4.4. Challenges of BSS in Buildings

The previous review highlights a research gap in biomimetic and self-shading literature, which often focuses on active rather than passive design. Challenges stem from gaps in research in the following areas:

- There is a significant gap in the scientific literature concerning the connection between biomimetic and self-shading, with most studies concentrating on biomimetic and kinetic facades.
- Modifying building shapes can effectively enhance self-shading and energy efficiency. Additionally, focusing on facade components is often more practical than making large morphological changes, which can restrict interior design flexibility. Furthermore, most prior studies prioritize building shape over facade components.
- Most evaluations of environmental performance indicators focus on heat gain, energy consumption, and daylight, indicating a lack of comprehensive assessment of other relevant indicators.
- Research on shading solid opaque façades is scarce, despite their vital role in building envelopes and their substantial influence on thermal performance and visual comfort indoors.
- The literature lacks a discussion on how brick patterns, geometric configurations, and various orientations affect the thermal performance of external walls.
- There is also a shortage of studies on the impact of different brick types and thicknesses on façade performance.
- Research is necessary to explore strategies for integrating multiple self-shading elements on facades and combining various patterns and configurations.
- Research on self-shading strategies' effects on urban climates and pedestrian pathways is scarce, despite their potential to reduce solar heat exposure for pedestrians.
- Many studies lack validation, undermining the credibility of their results and practical applicability.
- Current energy modeling tools have limitations that impede accurate assessments of dynamic façades and complex shapes.
- Finally, most studies are case-specific in their performance evaluations, highlighting the need for general guidelines applicable to diverse climates, orientations, shapes, and materials.

4.5. BSS Design Strategy

BSS seeks to implement sustainable building practices as an adaptive, eco-friendly strategy using a morphological approach. Designers can improve environmental performance indicators by examining how building shapes influence heat gain and loss. This section describes the phases of the BSS strategy, as illustrated in Figure 10.

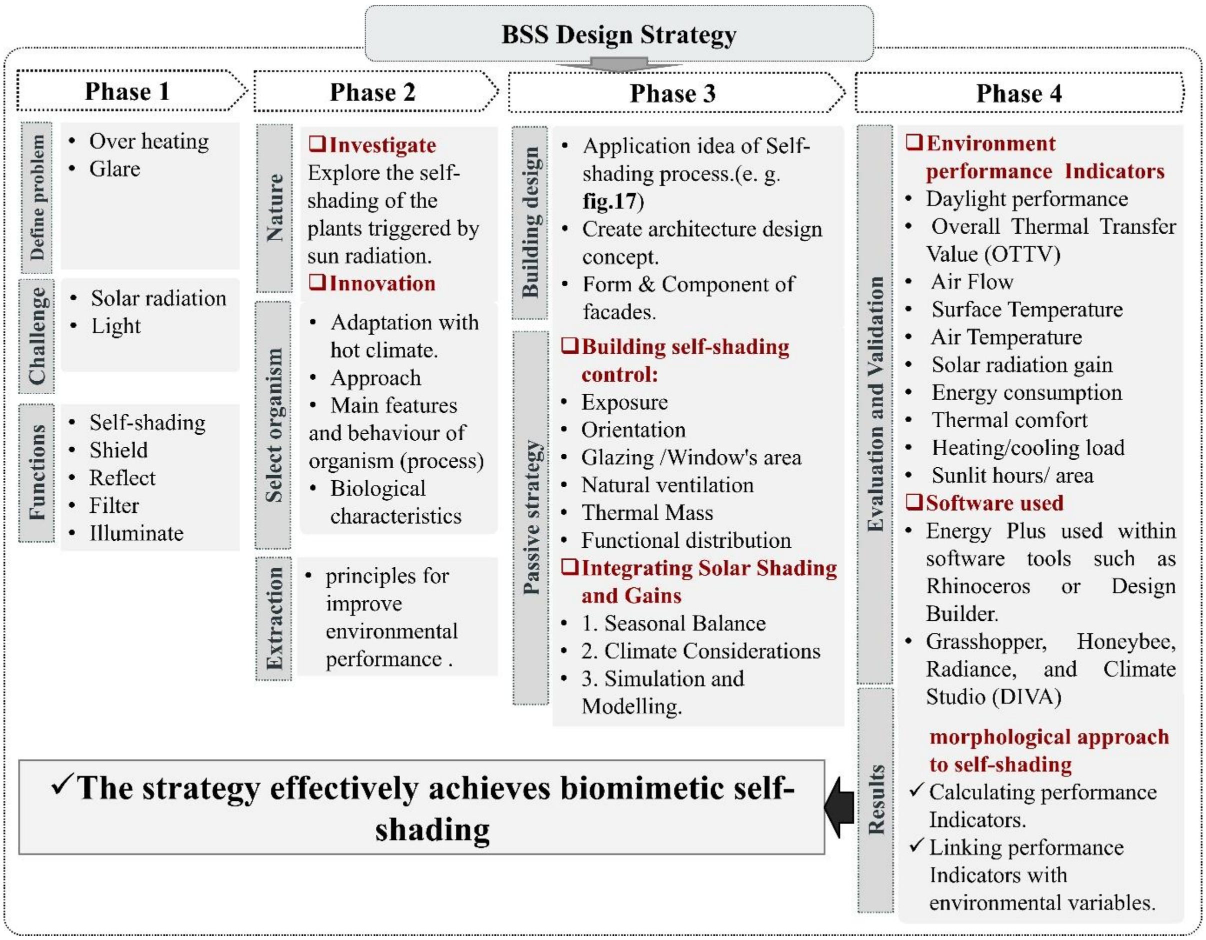


Figure 10.
Proposed BSS design strategy.
Source: The authors based on Shahda et al. [14], Faragalla and Asadi [99], Sommese et al. [55], Zhao et al. [107], and Kandar et al. [63].

The suggested strategy for BSS is complicated and includes the following stages:

- The first phase involves identifying problems such as overheating and glare caused by increased solar radiation, solving the balance between natural light and self-shading, and selecting the desired system functions, which include self-shading, filtration, and lighting.
- The second phase focuses on organism selection by investigating natural systems with self-shading habits and exploring innovative approaches to mimic these adaptations in design. The focus is on species that thrive in hot climates and their self-shading strategies, examining key characteristics of the selected organism, including morphology and physiological functions. Furthermore, this phase aims to define the basic principles of environmental performance.
- The third phase focuses on applying BSS ideas to building design, particularly by emphasizing the direction, shape, and thickness of self-shading elements. This includes shaping facades and selecting

materials and components to enhance the effectiveness of self-shading. It also highlights passive design strategies such as daylight, natural ventilation, material selection, orientation, and thickness. Seasonal solar changes and the site's specific climate are crucial for effective self-shading throughout the year. Simulation and modeling will be essential for evaluating the performance of self-shading in different scenarios.

- The fourth step involves the evaluation, validation, and reporting of results, beginning with the identification of environmental performance indicators. This stage utilizes software such as EnergyPlus, Grasshopper, and Honeybee to simulate the performance of the BSS model. Solar radiation, air temperature, useful light, and temperature are analyzed to measure environmental performance indicators.

This step-by-step strategy promises to integrate BSS into the design process from the initial stages, resulting in more sustainable, energy-efficient, and thermally comfortable environments.

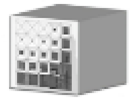
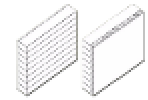
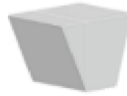
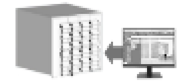
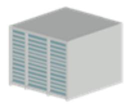
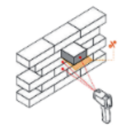
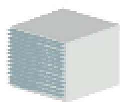
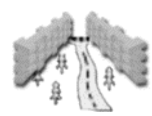
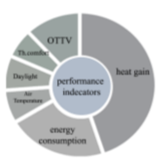
5. Conclusion

The main contribution of this study is to discover the connection between self-shading and biomimetic science through a comprehensive review of the previous literature and bibliometric analysis. This study investigates self-shading using a morphological approach based on façade components and the overall shape of the building. The study assessed previous research by relating challenges and opportunities in this field, which contributed to evolving a strategy for designing BSS buildings. The bibliometric analysis produced the following results:

- The number of publications in this field has increased since 2014, indicating continued interest in and research in BSS.
- The main research trends concentrate on keywords such as "biomimetics," "energy efficiency," "dynamic facades," "climate change," "shading systems," and "adaptive facades."
- The most cited works focus on adaptive building facade designs inspired by biomimetic principles. Among the prominent authors, Badarnah and Hosseni are the most prolific.
- The connection between self-shading and biomimetic science is an emerging topic of interest.
- BSS greatly influences internal solar radiation and heat transfer, temperature regulation, improving thermal comfort, and lowering energy consumption in hot, dry climates.

The bibliometric and systematic analysis submitted identified the focus of previous studies and the gaps listed in Table 6. These observations may serve architects and scholars in future studies. The BSS improves the environmental performance indicators. However, there are still important areas for exploration and enhancement. Continued research is essential for ensuring that biomimetic design remains relevant in sustainable architecture.

Table 6.
The analysis revealed the previous study's focus and gaps.

Most studies focus on :		**Research gaps**	
Biomimetic active shading (Kinetic & adaptive facades).		Self-shading of solid opaque façades.	
Self-shading through the overall building, including sloped walls combined with folded facades, has demonstrated the potential to reduce solar gain and improve daylight performance by more than 30%.		Brick patterns, geometric configurations.	
Some of these studies focus on unvalidated simulations.		Validation undermines the credibility of the results.	
Most studies involve a mix of opaque and transparent surfaces.		Offer practical design guidelines for various climates, orientations, shapes, and materials.	
Most studies use one method only for self-shading.		Self-shading through façade components & coupling more than one self-shading element & configurations on walls.	
Most studies involve assessment of the indoor environment only.		Effect of applying the self-shading strategy on the urban climate and pedestrian paths.	
Evaluation of heat gain, daylight factor, and energy consumption.		Evaluation of heating load in winter.	
Energy Plus is a assessment method widely used.		Energy modeling tools to assess dynamic facades and complex shapes.	

Key Abbreviations Used:

- Passive Design (PD)
- Active design (AD)
- Self-shading (SS)
- Kinetic façade (KF)
- Biomimetic façade (BF)
- Biomimetic self-shading (BSS)
- Overall Thermal Transfer Value (OTTV)
- Daylight Factor (DF)

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- Daylight Autonomy (DA)
- Spatial Daylight Autonomy (SDA)
- Daylight Glare Probability (DGP)
- Annual Sun Exposure (ASE)
- Continuous Daylight Autonomy (CDA)
- Useful Daylight Illuminance (UDI) / Comfort Time Ratio (CTR)
- Building Energy Demand (BED)
- Window-to-Wall Ratio (WWR)
- Physiological Equivalent Temperature (PET)
- Predicted Mean Vote (PMV)
- Predicted Percentage of Dissatisfaction (PPD)

Transparency:
The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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Appendix

Appendix 1.

1.1. Co- Occurrence of Keywords Analysis

Based on the relevance and level of development in research fields, the thematic map can visually display and categorize the author's keywords to comprehend research themes across four quadrants: niche themes, emerging or declining themes, motor themes, and basic themes, as shown in Figure 1. In this thematic map, the keywords "energy," "environmental impact," and "environmental regulation" represent specialized niche themes, indicating that they are focused and distinct areas of study.

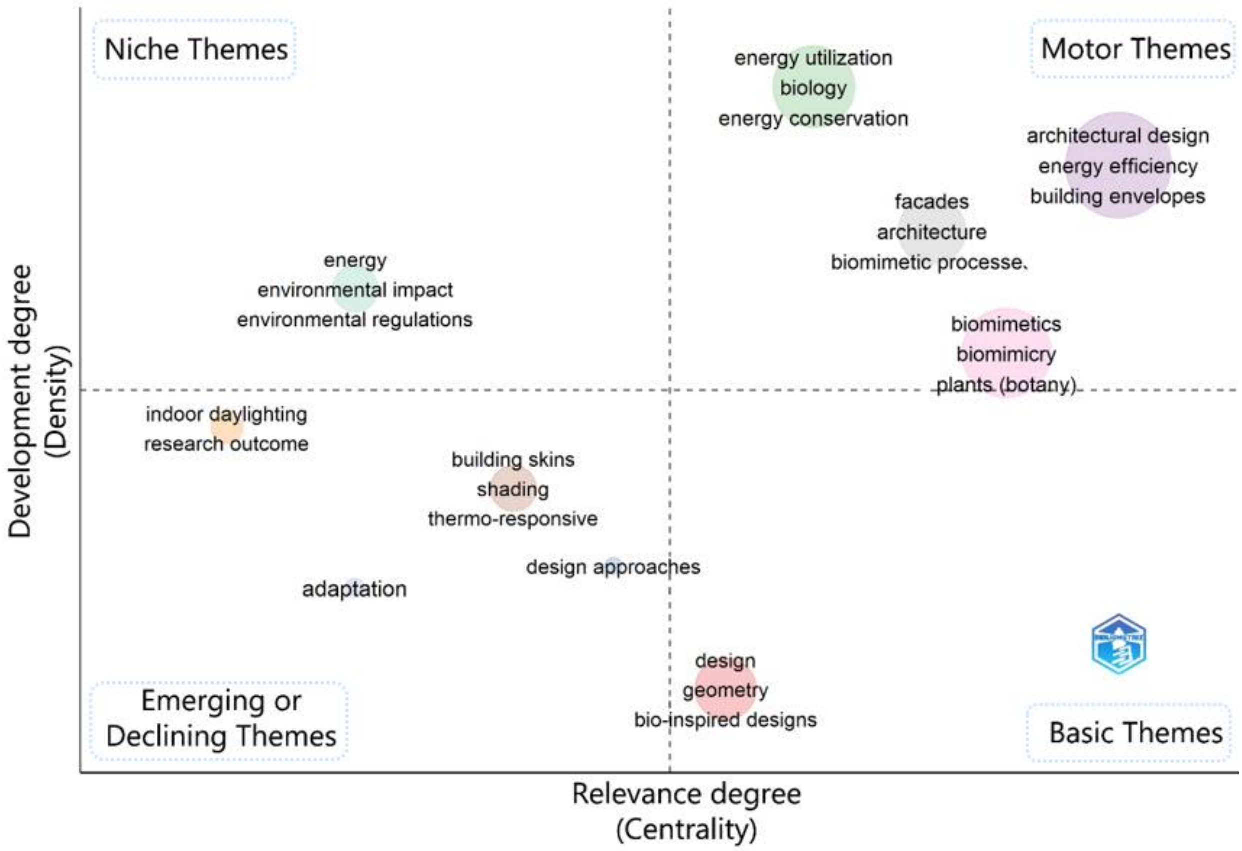


Figure 1.
A network map of keywords within a period (2014–2025): Thematic map based on the most frequent keywords.
Source: Based on the Scopus dataset using the biblioshiny tool.

However, the keywords "indoor daylight," "adaptation," "building skins," "thermo-responsive," and "shading" are considered emerging or declining themes. The keywords "biomimetics," "architectural design," "energy efficiency," "building envelopes," "biology," and "facades" can be identified as motor themes. These terms represent well-established and significant concepts within the field. Figure 2 shows the network visualization. During the past few years, most research areas have focused on the following keywords: biomimetics, energy efficiency, kinetic facades, climate change, shading systems, and adaptive facades.

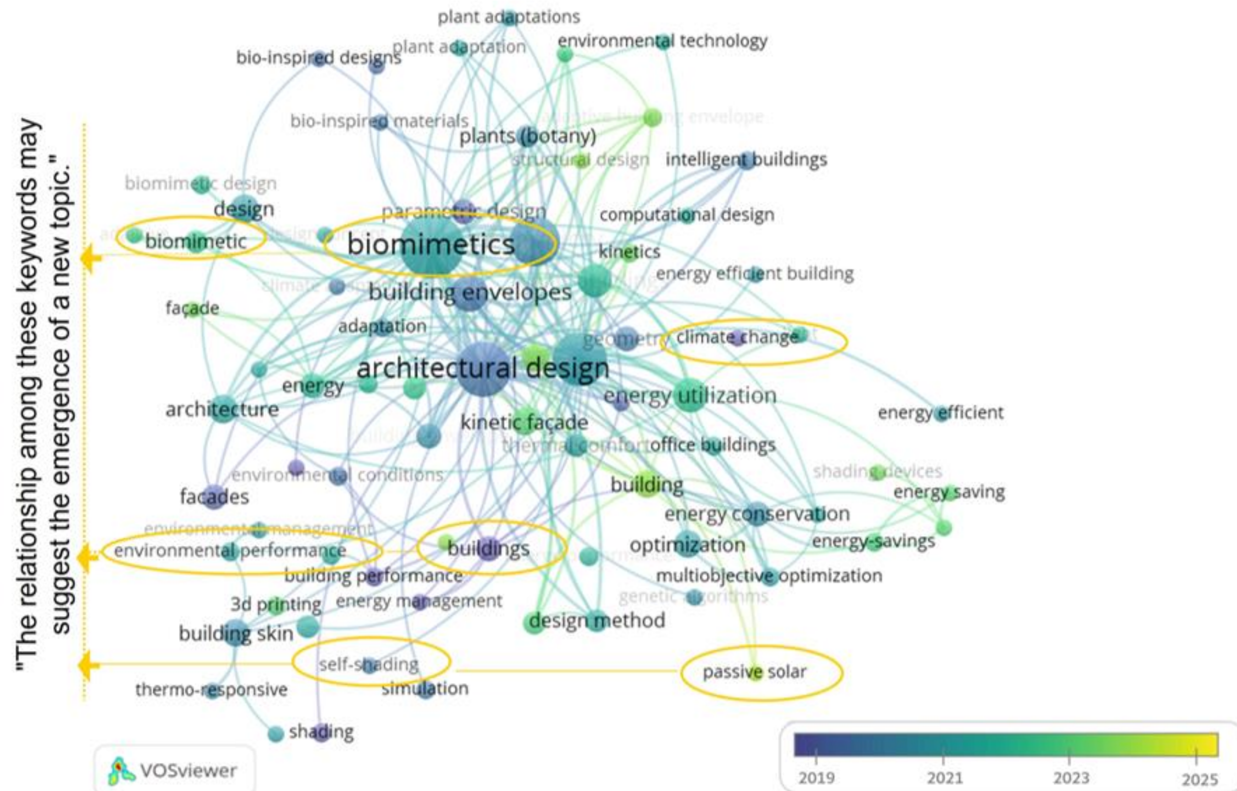


Figure 2.
Visualization of keywords' co-occurrence analysis by year.
Source: Based on the Scopus dataset using Vosviewer software.

It was found that most of the publications in this field, most of them recently, dealt with the active shading system using kinetic architecture, parametric design, and other adaptive facades according to climate change. Over the years, overlay visualization for co-occurrence analysis has shown an increasing trend in research examining the connection between biomimetic, kinetic, and adaptive facades. However, the connection between biomimetic and self-shading has received less attention. According to this, self-shading might be an emerging topic that needs more research.

1.2. Relevant Sources and Documents of Biomimetic and Self-Shading Publications

Figure 3 **(a)** presents the results of the top 10 sources focused on publishing articles on the study of biomimetic and self-shading. It turns out that "The Journal of Buildings" is the most relevant source, with 5 articles published [26, 43, 49, 104, 105]. This journal (JOB) has a TC index of 108, as shown in Figure 3 (a). The top quartile for this journal is Q1. Its scope includes all aspects of building science, engineering, and architecture. "Biomimetics," "Energy and Buildings," "Frontiers of Architectural Research," "Renewable and Sustainable Energy Reviews," and "Sustainability" are the second sources, and each of them contains 4 published articles [1, 3, 12, 13, 42, 45-48, 50, 103, 106-114] respectively. The Journal of "Biomimetics" is an international journal for the publishing of original research papers with a TC Index score of 22, as shown in Figure 3 (b). The top quartile for this journal is Q1 (Engineering, Multidisciplinary). It is a peer-reviewed, open-access journal on biomimicry and bionics, published monthly online by MDPI. The rest of the journals are concerned with energy use in buildings, the fields of architecture, and their relationship to sustainability.

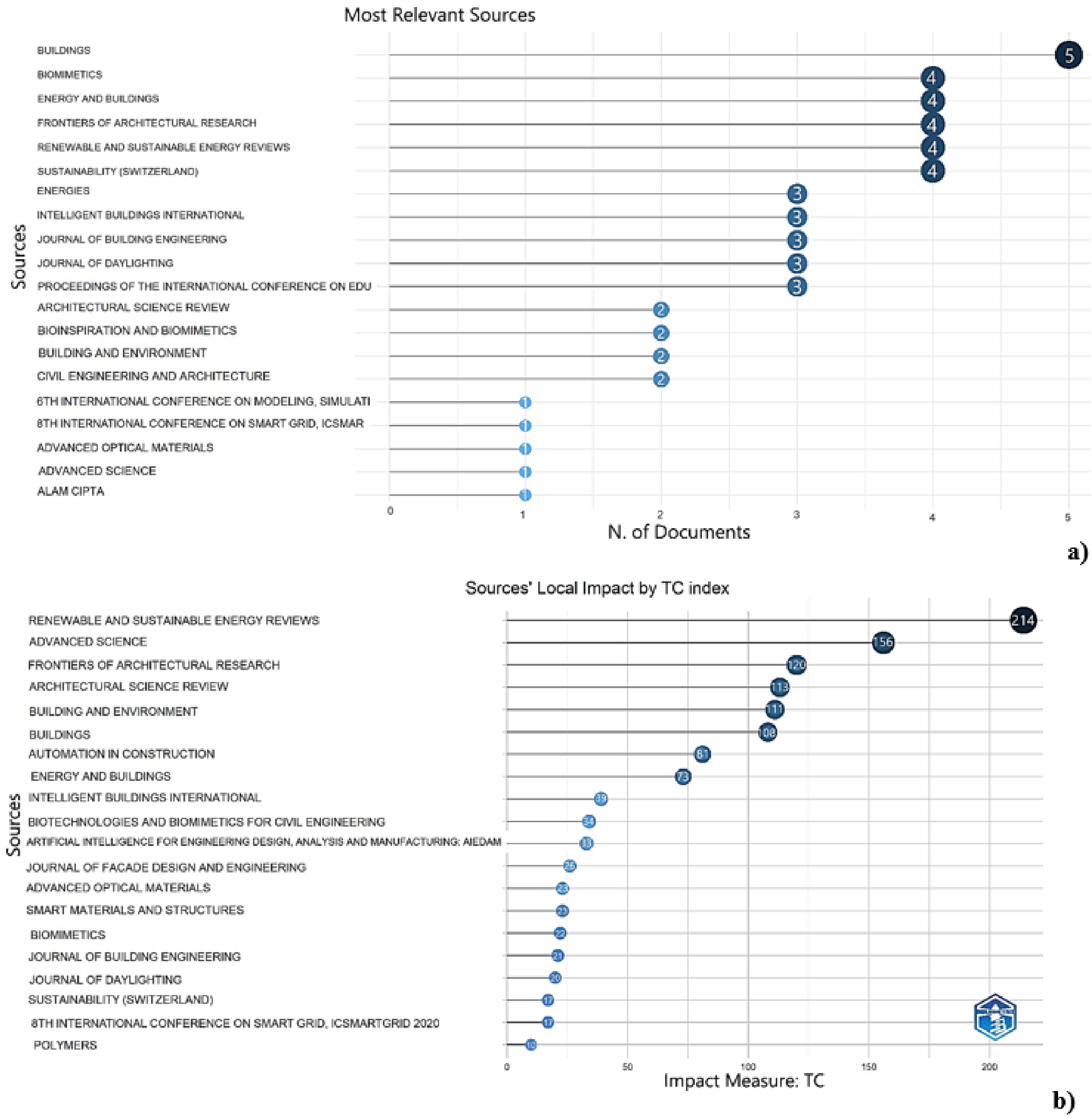


Figure 3.
(a) Relevant sources and documents based on the Scopus dataset; and (b) top 10 sources' total citations.
Source: Based on the Scopus dataset using the biblioshiny tool.

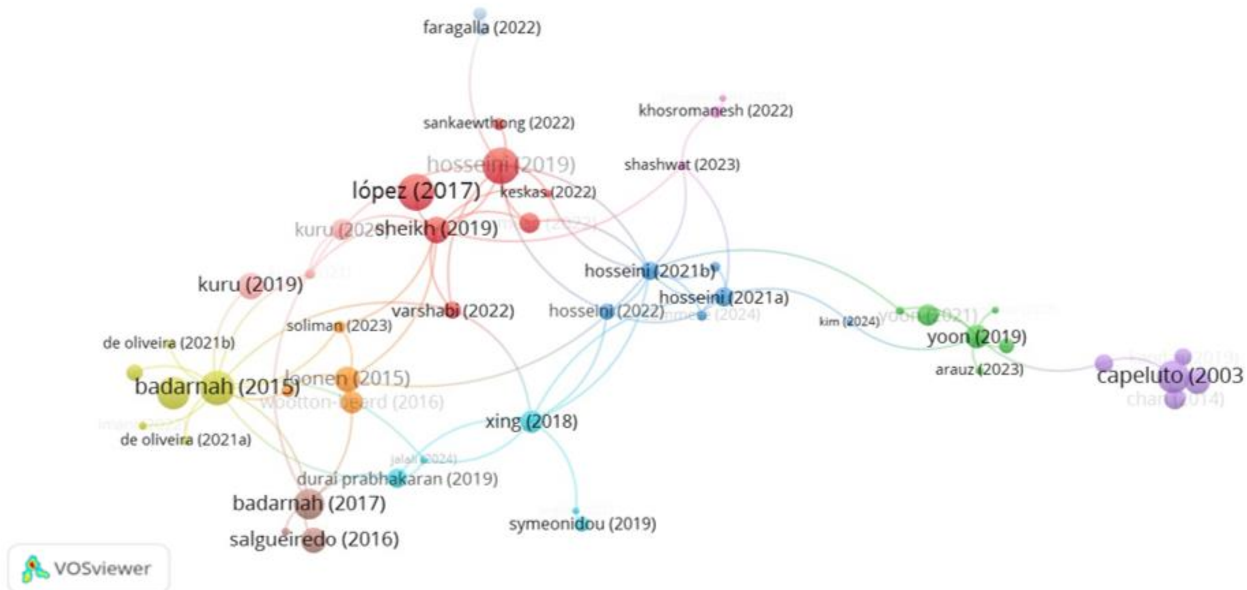


Figure 4.
Co-citation analysis for the most cited publications.
Source: Based on the Scopus dataset using Vosviewer software.

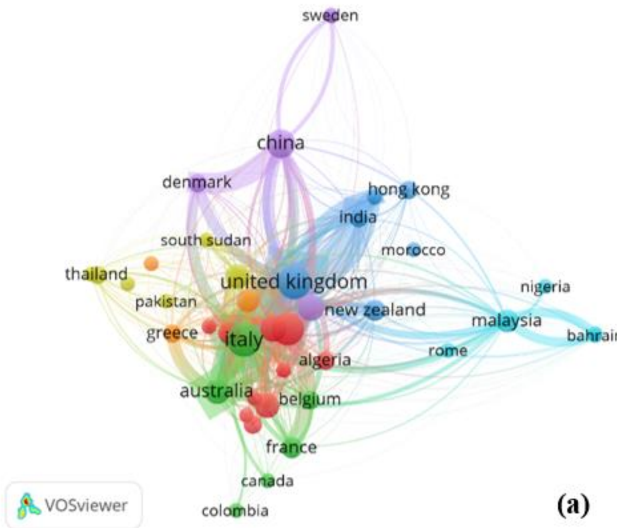
1.3. Most Cited Publications

Co-citation analysis was conducted to identify the most cited publications, a crucial indicator in an academic field [41]. As depicted in Figure 4 results were found for at least 80 citations.

The most cited publications were categorized into ten groups. The largest group (red) includes fourteen publications on biomimetic design for adaptive building façades, biomimetic principles, and bioinspired kinetic façade design [39, 47-49]. This group is closely related to the fourth (yellow) and fifth (purple) groups, as publications suggest design optimization of solar shading systems and mitigation and adaptation strategies [50, 115-118] toward a sustainable built environment [119, 120] using a control strategy [51, 121]. Furthermore, the second (green) and fifth (purple) groups cover design for thermo-responsive façade elements [45, 52, 112, 122] and wall self-shading technology [63] and its impact on the energy performance of building envelopes, [39, 57] respectively.

1.4. The Network of Prominent Countries

The analysis examined scientific output, emphasizing publication and contributions across various regions and countries in the study field. The results identified the 30 most prominent countries, as shown in Figure 5 (a). While The top 10 countries made notable research contributions, as shown Figure V in (b). Italy led the list with 40 publications, followed by the UK with 35. In addition, the study noted some contributions from countries like China, the USA, Australia, and the Netherlands in biomimetic and self-shading research. However, many countries with arid desert climates should increase their contributions to such research.



N.	Region	No. of publications
1	ITALY	40
2	UK	35
3	CHINA	17
4	NETHERLANDS	15
5	USA	14
6	AUSTRALIA	13
7	EGYPT	12
8	PORTUGAL	11
9	MALAYSIA	10
10	FRANCE	9

(b)

Figure 5.
(a) Bibliographic coupling countries about 42 countries (Source: Based on the Scopus dataset using Vosviewer software) & (b) The top 10 countries in the scientific production of biomimetic and self-shading (Source: Based on the biblioshiny tool)

1.5. The Network of Authors And Prominent Authors

As shown in Figure 6**,** the size of the circles, which represent the authors' relevance, can be used to identify the authors' network based on the number of writers' citations. The lines connecting the researchers indicate the number of co-authorship linkages, and the degree of association between two things determines their distance.

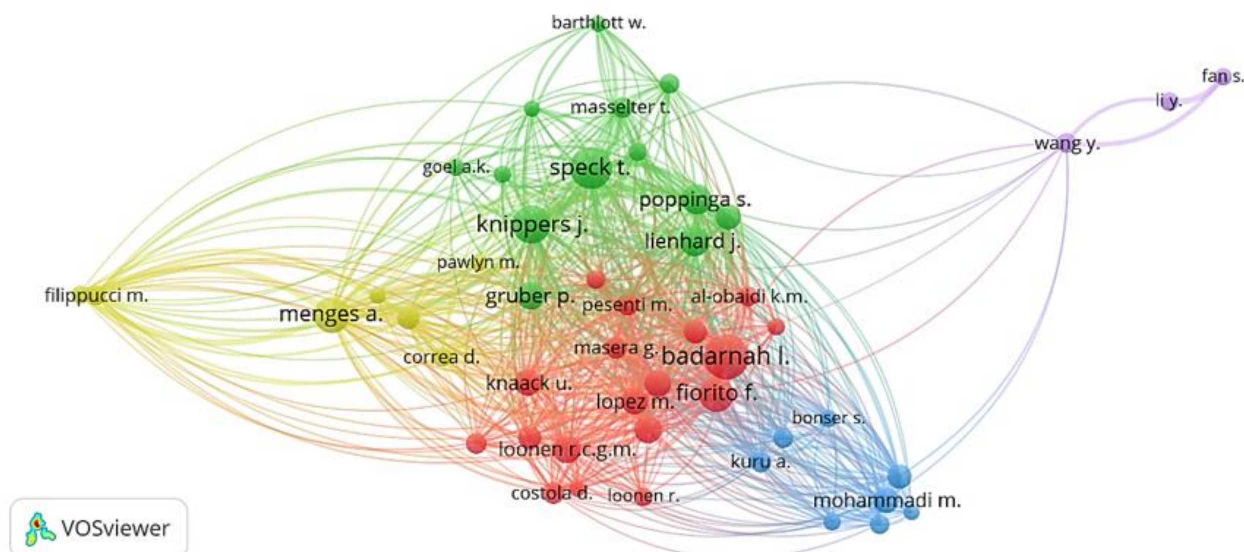


Figure 6.
Bibliometric analysis of the networks of the 50 most prominent authors.
Source: Scopus dataset analyzed with Vosviewer software.

The author's network consists of five clusters: the red cluster has eighteen authors, the green cluster contains thirteen, the blue cluster contains eight, the yellow cluster contains seven, and the purple

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cluster contains three. The most cited authors in each cluster are Badarnah L. (130 citations), Speck T. (114 citations), Mohammadi M. (49 citations), Menges A. (86 citations), and Wang Y. (38 citations), respectively.

On the other hand, Figure 7 presents the top 25 authors' production over the years, showing the number of articles (circle's size) and total citations per year (circle's color). Badarnah L., Senior Lecturer of Architecture and the Built Environment (ABER), is the most prominent. Her work contributes to an emerging area that seeks to redefine environmental design in architecture through biomimetic. Hosseini SM, the research associate at Imperial College London, stands out as the most productive author, with a substantial number of documents exploring biomimetics and its connection to architecture.

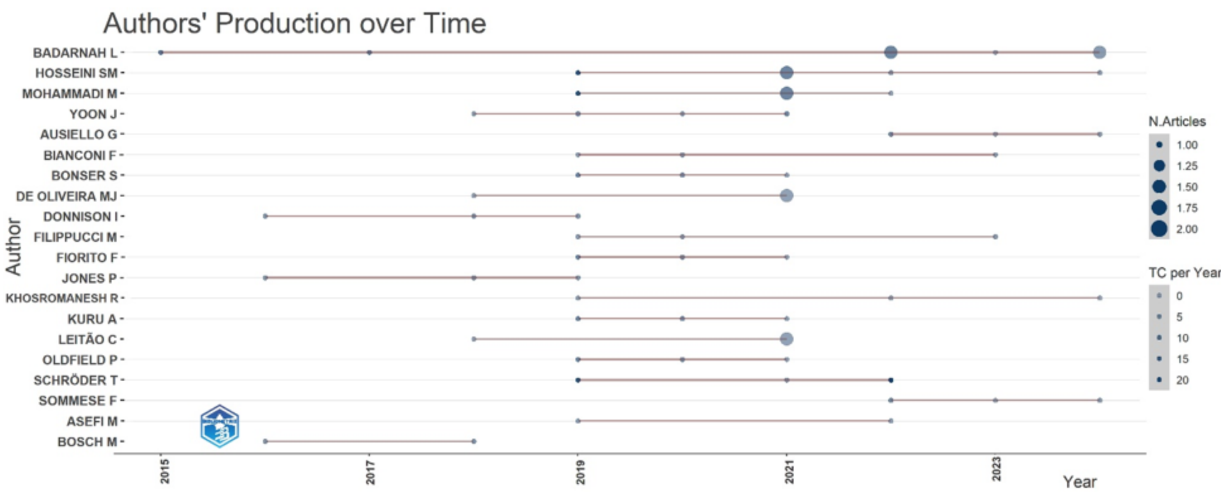

Figure 7.
Bibliometric analysis of authors: top 20 authors' production over the years.
Source: Based on the biblioshiny tool.

Based on the authors' impact regarding overall total citation, Badarnah L. is the most cited author, as shown in Figure 8 (a), whereas her citations reach 183 in the research scope. Regarding the authors' H-Index, Badarah L., Husseini SM., and Yoon J. achieve the highest value in the research field, which stands at 4, as indicated in Figure 8 (b).

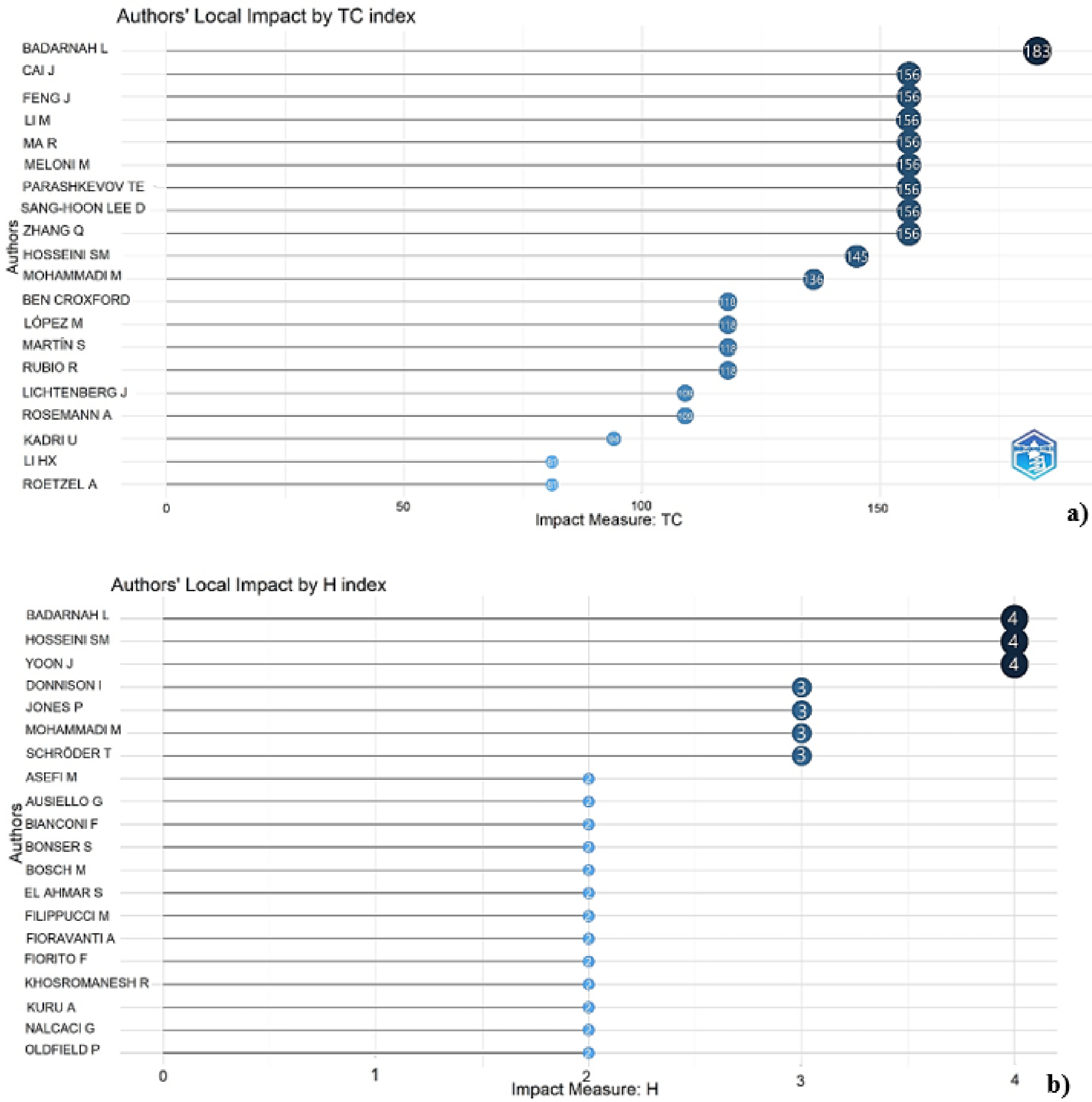

Figure 8.
Bibliometric analysis of authors' impact: (a) total citations; and (b) H-Index.
Source: Based on the biblioshiny tool.

It is worth noting that the term "biomimetic self-shading" has not been extensively discussed in previous research on this topic. Prominent keywords linked to esteemed authors and sources include "biomimetic," "building skins," "thermal comfort," and "kinetic facades." These themes are closely associated with the 20 most significant sources highlighted in the red cluster of Figure 9.

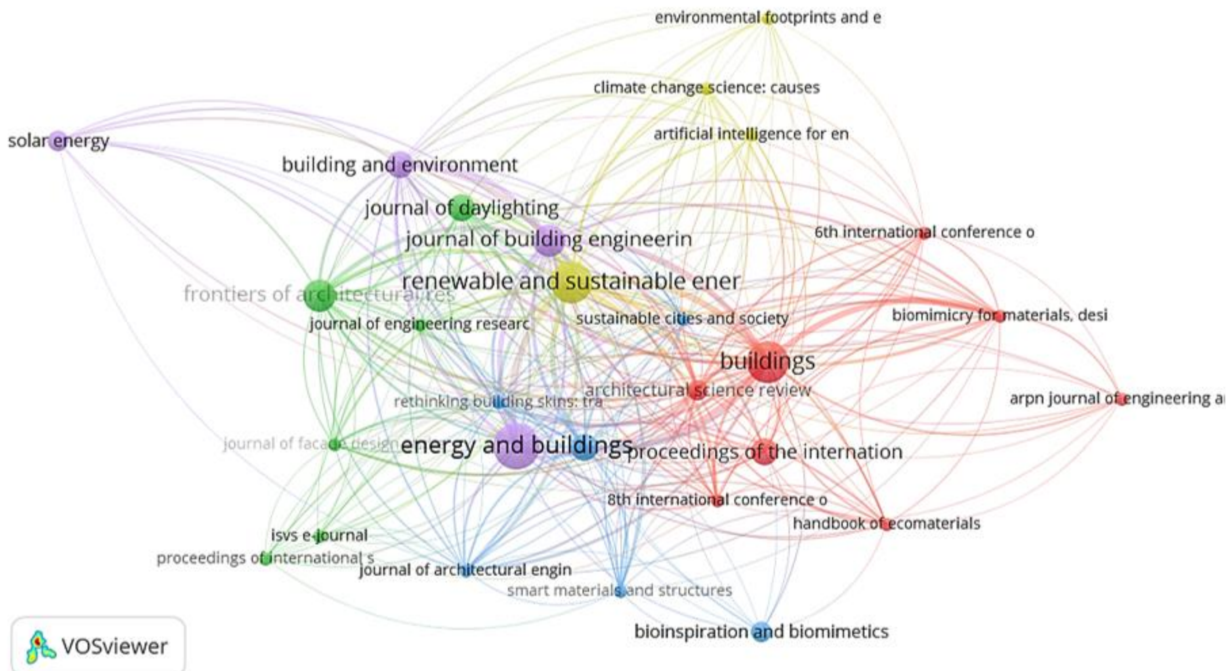

Figure 9.
Bibliometric analysis of sources: 20 most prominent sources' networks by the number of documents
Source: Based on the Scopus dataset using Vosviewer software.

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