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Biomimetic adaptive solar building envelopes: Trends, challenges, and opportunities for sustainable applications

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ABSTRACT

As global energy demand continues to rise, the importance of effective solar management in building design becomes increasingly critical. Solar management encompasses strategies for harvesting, regulating, and utilizing solar energy, contributing significantly to sustainable and renewable energy solutions. Biomimetics presents a promising approach to adaptive design by drawing inspiration from nature's solar management strategies. This research conducts a systematic review of biomimetic adaptive solar building envelopes (Bio-ASBEs), classifying them into three key solar management strategies: solar regulation, solar harvesting, and thermoregulation. A comparative analysis of existing studies highlights trends, gaps, and opportunities in the field. Findings indicate growing interest in biomimetic solutions for solar management, with a predominant focus on energy efficiency. However, the study identifies limited research on energy harvesting and indoor environmental quality, as well as a reliance on shading techniques, potentially overlooking alternative thermoregulation and solar harvesting strategies. Furthermore, the study highlights the scarcity of mixed-method research, emphasizing the need for multifaceted approaches that integrate, qualitative and quantitative data into actionable solutions. Finally, this study reveals the untapped potential of biomimetic solar management strategies, demonstrating how integrating solar harvesting, regulation, and thermoregulation can drive the development of adaptive, energy-efficient building envelopes. By bridging research gaps and exploring nature-inspired multifunctional solutions, it paves the way for scalable, climate-responsive technologies that support net-zero goals and a more sustainable built environment.

1. Introduction

The concept of the building envelope is improving to the extent that it can be considered as a 'climate controller' as well as an energy generator. Reflecting, harvesting, storing, converting energy diffusing light, and providing shading, comfort, protection, and visibility are among the means by which a building envelope can respond to solar emissions [1]. One of the challenges is that some of the requirements a building needs to fulfil are often conflicting, such as thermal inertia and light-weight structure or maximum daylight optimization and glare protection [2]. Nature deals with similar problems successfully and adopts a variety of strategies to reach an optimum solution [3,4]. Solar energy which is one of the important natural and renewable resources can be managed through the building envelope in ways that can be inspired by countless adaptive strategies in nature [5]. Nature facilitates solar regulation, solar harvesting and thermoregulation [6]. In this study, Biomimetic Adaptive Solar Building Envelope (Bio-ASBE) is defined to refer to a building facade or skin (including vertical and horizontal enclosures) designed to regulate and/or harvest solar radiation by drawing on relevant strategies from nature. Light responsiveness by mimicking natural strategies has multiple implications in architecture, one of which is related to general aesthetic aspects [7,8]. For instance, automated shading systems' function is not only to filter excessive light but also the filter's motion can improve the aesthetic architectural experience as well [9]. In this regard, within a specific context, Lenau et al. [10] argued that solar cells can be used widely if their appearance is close to the traditional red clay tile. To fulfil this purpose, they used mathematical and empirical methods and analysed the effect of colouring solar cells. Eventually, they proposed to use structural coloured filters inspired by biological structures [3]. Using decorative elements like films that may be printed or perforated to express specific patterns in front of the solar cells is another way to make them aesthetically pleasing; however, printed glass covers or coloured encapsulants suffer from high power loss or low colour saturation. Therefore, Blasi et al. [11]proposed a photonic colour concept inspired

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Abbreviations

Bio-ASBE	Biomimetic Adaptive Solar Building Envelope
QL:	Qualitative
QN	Quantitative
M	Mixed
EE	Energy efficiency
TC	Thermal comfort
VC	Visual comfort
EH	Energy harvesting
IEQ	Indoor environmental quality
DL:	Daylighting
SH	Solar harvesting
TRL:	Technology Readiness Level
PV	Photovoltaic
NM	Not Mentioned

by the Morpho butterfly for integrated photovoltaic modules. They demonstrated how a Morpho structure inspired by nature can transmit a large fraction of solar radiation to solar cells and at the same time enhance stability and colour saturation [11].

Building materials also can provide various opportunities for designing a solar responsive façade [12]. Along this path, the Eskin project has achieved interesting aesthetic qualities as well as minimal energy consumption by engineering adaptive materials inspired by the sensory-adaptive feature of human epithelial cell [13]. The Thematic Pavilion designed by Soma architects at Expo 2012 is another example of a light-responsive façade that not only controls daylight conditions but also features aesthetic aspects of lighting effects. The dynamic system was inspired by the kinetic system principles of Strelitiza reginaee flower [14]. In this context, this paper aims to identify trends, gaps, and opportunities in the field of biomimetic adaptive solar building envelopes (Bio-ASBEs) and solar management strategies through a systematic review. This study focuses on biomimetic studies addressing solar adaptation solutions among other environmental adaptations, offering a novel contribution on identifying the current gaps, limitations and opportunities, and presenting synergies between the building envelope and nature. Section 3 provides contextual information about the field and provides a classification of these solutions, identifying three primary aspects of biomimetic solar adaptation strategies. In Section 4, the results of the bibliometric and comparative analyses are presented, uncovering patterns, trends, and gaps within the field. Finally, Section 5 discusses challenges, opportunities, and future pathways, offering valuable insights to guide the development of innovative and sustainable building design strategies.

2. Methodology

The focus of this study lies at the intersection between three domains: Adaptive Building Envelopes, Solar Adaptation Strategies, and Biomimetics as shown in Fig. 1. This review looks at the existing publications in this area and their strategies that provide solar management in buildings inspired by nature.

2.1. Data identification and screening

Relevant keywords were defined to guide data identification based on the focus of this study at the intersection of three domains, listed in Table 1. The identification and screening followed a systematic approach [15] as presented in Fig. 2, using NVivo software for managing and analysing the literature. The selected studies had to meet the following criteria for inclusion.

- The studies on adaptive solar envelopes should have a biomimetic approach to address the novelty of the current review
- All the studies that meet the first criteria and address solar management in buildings including solar regulation, solar harvesting, and any kind of integrated solutions to manage light and energy are included in the study group.
- The studies using languages other than English are excluded from the current review

Table 1
Systematic searching approach (updated in February 1, 2024).

Search within title, abstracts, keywords	Database	Numbers of studies
“Biomimicry” OR “biomimetic” OR “bio-inspired” OR “inspired by nature” AND “solar” OR “shading” OR “light” AND “building” OR “façade" OR “building envelope” OR “architecture” OR “building skin” AND “Adaptive” OR “adaptation” OR “responsive” OR “smart” OR “intelligent” OR “regulate” OR “regulation” OR “harvest” OR “kinetic” OR “dynamic” OR “daylighting"	Scopus	283

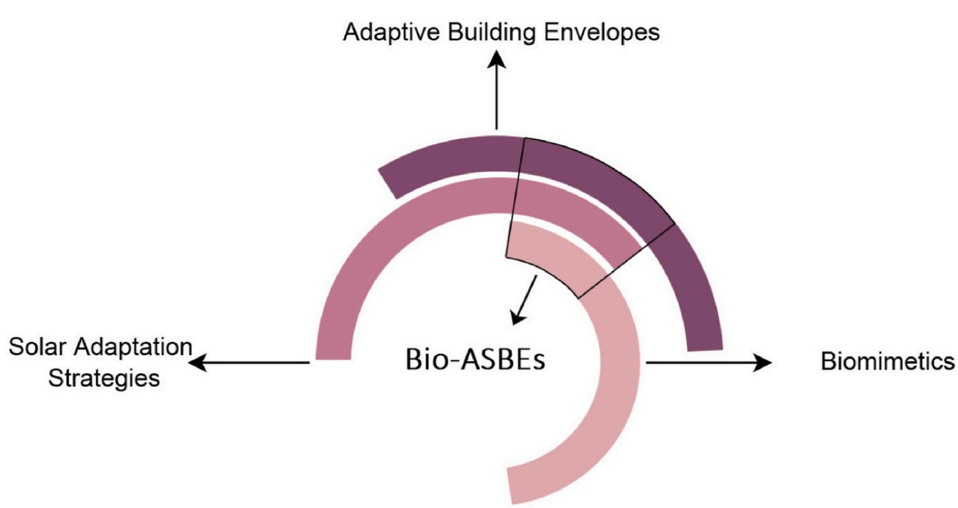

Fig. 1. Study area of this review at the intersection of domains; Adaptive Building Envelopes, Solar Adaptation Strategies, and Biomimetics.

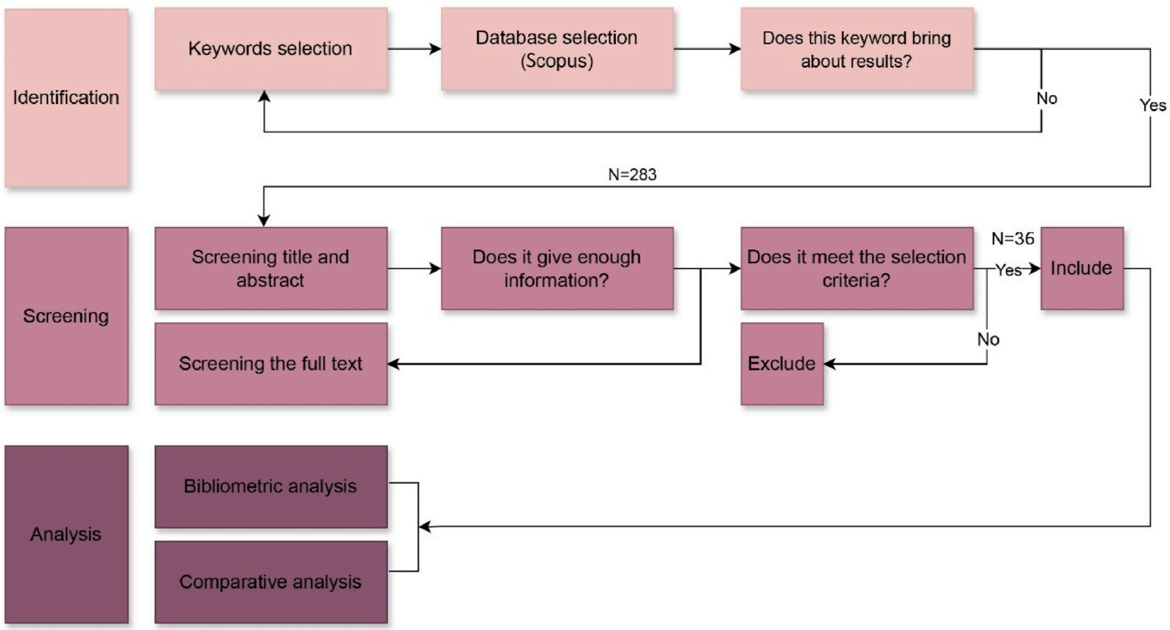

Fig. 2. Systematic data inclusion and exclusion.

2.2. *Analysis criteria*

This research employs parameters' classification facilitating the comprehensive identification of various aspects within each study. The analysis criteria are defined based on an inductive approach, distilling relevant aspects from the background in section 3. This approach ensures a smoother and more consistent comparative analysis across all the selected studies by using uniform parameters. Additionally, this helps highlight trends, gaps, and opportunities within the research landscape, ultimately advancing our understanding and application of Bio-ASBEs in architecture. To do so, comparative analysis graphs (section 4) are generated using Python programming language, utilizing the Seaborn and Matplotlib libraries. Moreover, Bibliometric analysis for keyword co-occurrence is conducted using VOSviewer [16] which is a software tool for constructing and visualizing bibliometric networks.

The methods employed in studies vary based on their specific contexts and are categorized into qualitative, quantitative, and mixed methods because each of these approaches plays a distinct role in overcoming key challenges in biomimetic research, as identified by Ref. [17]. These challenges include.

1. Identifying suitable biological models, which requires determining what, where, and how to search during the bio-inspiration process.
2. Assessing the relevance of identified models to ensure alignment with the specific design problem.
3. Understanding and interpreting biological data, translating complex biological information into actionable design insights.

3. Adaptive solar building envelopes

This section provides an overview of the relevant definitions and introduction to biomimetic solutions for adaptive building envelopes, focusing on solar adaptation strategies and their architectural analogues. This approach narrows down the application of biomimetics to how building envelopes can adapt to solar radiation, similar to how natural organisms respond to solar conditions.

3.1. *Adaptive building envelopes*

Traditionally, the building envelope has been conceived as a barrier separating the interior from the exterior environment. However, the growing need for energy consumption reduction has prompted a re-evaluation of the envelope's role, where the building envelope is conceived as a multifunctional medium with responsive capabilities [1,18]. The concept of adaptive building envelope has been discussed under various terminologies in literature. One of the earliest instances of the term "adaptive façade" (AF) appeared in 2007 [19,20]and since then, the idea has evolved, encompassing different terminologies such as adaptive building skin [21], climate adaptive building envelope [22], and adaptive building façade [23].

Adaptive building envelopes are designed to dynamically respond to varying climatic conditions over daily, seasonal, or annual cycles [24]. This adaptability is aimed at enhancing occupant comfort and well-being while optimizing energy performance. Solar responsiveness in building envelopes can be achieved through a range of technologies and materials that either passively harness or actively manage solar energy. Some of the solar control material and technologies are presented in Table 2. The control mode is categorized into four types: static, which have fixed properties and do not change dynamically or respond to external factors; responsive, which have the capacity to react to external stimuli through changes that do not involve the physical movement of parts; and responsive and dynamic, which refers to systems that dynamically adjust in response to external stimuli.

3.2. *Biomimetics*

The terms "biomimetics" and ""biomimicry" are often used interchangeably in the literature, although subtle distinctions can be drawn. Biomimicry, as introduced by Benyus in her seminal book *Biomimicry: Innovation Inspired by Nature* [35], views nature as a model, measure, and mentor. Benyus highlighted the transformative potential of mimicking nature's systems, forms, and processes to address human challenges, such as sustainable design and energy efficiency, fostering a healthier and more sustainable planet.

Biomimetics in design typically follow two main approaches: a solution-based approach, where biological discoveries inspire innovative design solutions; a problem-based approach, where a specific technological challenge prompts designers to seek analogies in nature for inspiration. In terms of solar adaptation, Badarnah [36] identified notable natural mechanisms that regulate light through processes such

Table 2
Applications of solar control materials and technologies.

Aim	Materials and technologies	Control mode
Optimizing the incident visible light transmission	Anti-reflection layers, Optiwhite glass [1]	Static
Protecting the internal environment from excessive overheating	Solar control glazing, Reflective coatings, Tinted glass [1]	Static
Reducing the thermal losses to the outside	Vacuum glazing, Low-E coatings, Geometric media, Aerogels, Low-E coatings [1]	Static
Passing light from the window deeper into the rooms	Prismatic structures, reflective lamellae, light shelves, laser cut panels [1]	Static
reducing the risk of excessive contrast and disability glare	Double Glazed Units with integrated protective blinds [1]	Static
Passive changing the optical properties of the glass flexibly	Thermochromic glass, photochromic gasochromic glass [1]	Responsive
Active changing the optical properties of the glass flexibly	electrochromic, Suspended Particle devices, Liquid Crystal Displays [1]	Responsive
Energy-harvesting	Building integrated photovoltaics [25] with sun tracking	Responsive and dynamic
Temperature responsiveness	Thermo-Bimetal [26], Shape memory alloys [27,28], Thermochromic polymers [27,29], Phase Change Material (PCM) [30]	Responsive and dynamic
Light responsiveness	Phosphorescence pigments [31], Light, Responsive Polymers [32,33], Photochromic dyes [31–34,34]	Responsive

as illumination, filtration, and harvesting, providing a foundation for integrating nature-inspired principles into architectural applications. The study by Sommese et al. [37] on a bio-adaptive model incorporated solar-responsive functionalities in building envelope design, linking adaptive responses such as regulating, shielding, reflecting, storing, and transforming solar energy to environmental stimuli like sunlight and temperature, thereby creating a framework for dynamic and efficient solar management in architecture. Building on these insights, Jalali et al. [6] developed a design framework for solar building envelopes inspired by plant behaviours [5], focusing on the systematic analysis of plant adaptations to various climatic conditions, and providing recommendations for the incorporation of different photovoltaic technologies.

3.3. *Biomimetic adaptive solar building envelopes*

The design of biomimetic adaptive solar building envelopes (Bio-ASBEs) draws inspiration from nature, emulating solar adaptation strategies developed through millions of years of evolution. These designs address critical building challenges, such as insufficient daylight, excessive glare, and overheating, by leveraging biological analogies to create solutions that adapt to environmental changes.

Adaptive solar solutions for building envelopes range from concepts to physical prototypes of real applications, as presented in Fig. 3. Homeostatic Façade (Fig. 3, a) is inspired by the way that muscles work and automatically responds to temperature variations [41]. This dynamic adaptation can helps regulate a building's internal temperatures, improving thermoregulation and reducing the need for mechanical heating or cooling. Likewise, Air Flow(er) (Fig. 3, b) is an actively responsive device that opens when exposed to warmer temperatures to regulate airflow and interior temperature [42] Inspired by the principles of flowers' behaviours [86], this system can contribute to buildings' thermoregulation by improving ventilation and passive cooling. Hygro-skin (Fig. 3, c) is a biomimetic design for a facade system which is responsive to humidity using the inherent capacity of the material and adjusts the degree of porosity modulating the visual permeability and light transmission of the envelope [43]. In addition to shading, the material's ability to change porosity with humidity can improve thermal performance, reducing heat transfer and maintaining comfortable indoor temperatures. Similarly, Solar Gate (Fig. 3, d), a bio-inspired and bio-based weather-responsive shading system is developed using 4D printing techniques [44].

The solar management strategies in nature encompass three key functions: harnessing, illuminating, and filtering [36]. The parallels between natural systems and building envelopes is presented in Fig. 4, highlighting how principles observed in nature can inform innovative approaches to building envelope design for solar management.

In nature, features like reflective surfaces, pigment changes, and structural adaptations regulate solar gain and heat dissipation, ensuring organisms maintain optimal internal conditions. Similarly, building envelopes employ shading devices, thermochromic materials, and reflective coatings to manage solar energy for improved energy efficiency and occupant comfort. These parallels highlight the potential of biomimetic approaches in advancing building envelope technologies, leveraging nature's time-tested strategies to create more efficient and sustainable designs. The following sections further elaborate on the key

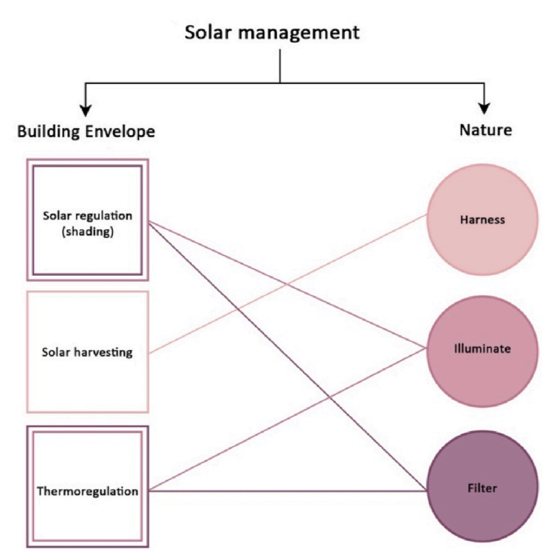

Fig. 4. Solar management potential synergies between building envelopes and nature.

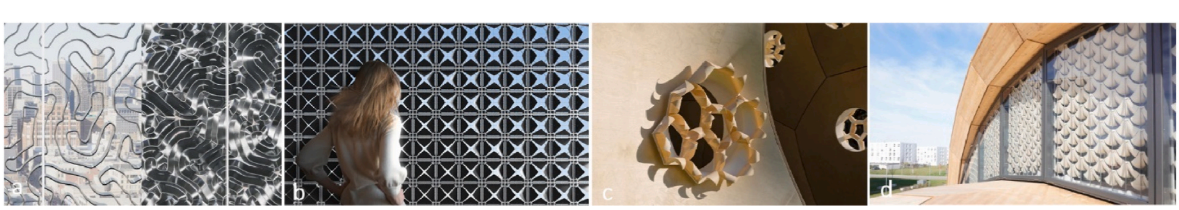

Fig. 3. Examples of biomimetic adaptive solar building envelope solutions. (a) *Homeostatic Façade* [41] ©Decker Yeadon *LL. C*; (b) *Air Flow(er)*, Image by Andy Payne/LIFT architects [42]; (c) *Hygro-skin* ©ICD University of Stuttgart [45]; (d) *Solar Gate* ©ICD University of Stuttgart [46].

aspects for potential synergies, i.e. solar regulation, solar harvesting, thermoregulation.

3.3.1. Solar regulation

Nature offers diverse mechanisms for regulating solar radiation to maintain optimal internal conditions, including the dynamic orientation of leaves and reflective properties of plant surfaces. For example, heliotropic plants like sunflowers adjust their orientation to optimize solar exposure based on environmental needs. These natural strategies inspire biomimetic design solutions, such as kinetic facades and thermochromic materials, which adapt dynamically to changes in solar angles and intensities.

In building design, solar regulation plays a crucial role in enhancing daylighting and energy performance. Shading systems directly impact these factors by minimizing overheating and improving daylighting, reducing reliance on artificial lighting and cooling systems [2]. For instance, the orientation of leaves in plants, optimized to capture light for photosynthesis or to reduce heat stress, provides a model for building envelopes that respond dynamically to solar radiation.

Additionally, nature-inspired approaches can avoid self-shading, as observed in certain plants where lower leaves rotate horizontally to minimize shading from upper foliage [47]. This strategy could inform innovative building designs that optimize sunlight exposure, resulting in a balance between energy efficiency and occupant comfort. By integrating adaptive elements inspired by these biological principles, architects and engineers can develop shading systems that effectively address the dual challenges of solar regulation and energy optimization.

3.3.2. Solar harvesting

Solar harvesting in nature involves mechanisms such as photosynthesis in plants, which converts solar energy into chemical energy, and thermoregulation in animals like lizards, which absorb heat to maintain body temperature. Nature also offers specific examples for solar harvesting optimization. Buttercup flowers reflect sunlight toward their reproductive organs through petal morphology [48], while certain plants adapt to varying sunlight conditions by optimizing their exposure [4] The honeycomb microstructure on butterfly wings traps solar energy through total internal reflection, inspiring an adaptive design that adjusts panel shapes to concentrate heat in winter and minimize heat loss at night [49].

Biomimetic innovations have significant potential to enhance advanced energy-harvesting technologies in the building industry. For example, building-integrated photovoltaics (BIPVs) already play a pivotal role in generating electricity through solar energy. By incorporating biomimetic principles, these systems can achieve improved efficiency, better integration with architectural designs, and enhanced performance, further advancing the role of solar harvesting in sustainable building envelopes [6].

3.3.3. Thermoregulation

Thermoregulation in nature offers valuable insights into managing solar radiation. Desert plants like *Encelia farinosa* use reflective silvery hairs to reduce heat absorption under stress, while plants such as *Phlomis* and *Coleus argentatus* employ waxy or hairy surfaces to enhance reflectivity [6,50,51]. Inspired by these strategies, building materials with high reflectance and adaptive optical properties can improve thermal performance. In animals, features like the reflective compound eyes of decapod crustaceans and the structural coloration of the Morpho butterfly demonstrate efficient light and heat management [52,53]. These mechanisms inform technologies like color-changing façades that adapt their reflectivity to control heat gain, as seen in chameleon-inspired systems [54].

Advanced materials further exemplify biomimetic thermoregulation. For example, radiative cooling glass, modelled on beetle cuticles, reflects near-infrared radiation and emits heat while maintaining transparency, reducing temperatures by up to 18.1 °C and cutting energy use by 23.4 % [55]. Similarly, coatings inspired by poplar leaf hairs or the African reed frog's reflective skin regulate solar absorption and heat transfer [56,57]. Translating these natural strategies into building envelope designs allows biomimetic solutions to effectively thermoregulate, manage solar radiation, and enhance energy efficiency and occupant comfort in sustainable architecture.

4. Results

This section provides an overview on the classification criteria (4.1) and the results of the bibliometric (4.2) and comparative analysis (4.3–4.12), investigating existing trends, challenges, and opportunities.

4.1. Definition of classification criteria for comparative analysis

The background in section 3 of this study has provided relevant insights into the classification criteria chosen for the analysis presented in Table 3. This study distinguishes between qualitative, quantitative, and

Table 3
Classification criteria for the analysis of Bio-ASBE studies.

Category	Classification		Abbreviation
Method	Qualitative		QL
	Quantitative		QN
	Mixed (qualitative and quantitative)		M
Approach	Bottom up		Bu
	Top down		Td
Challenge	Energy efficiency		EE
	Thermal comfort		TC
	Visual comfort		VC
	Energy harvesting		EH
	Indoor environmental quality		IEQ
	Daylighting		DL
Performance	Solar regulation		S
	Solar harvesting		SH
	Thermoregulation		Th
Climate	Tropical		A
	Arid		B
	Temperate		C
	Continental		D
	Polar		E
Context	External		Ext
	Internal		In
	Integrated		It
Adaptation mode	Passive		P
	Active		A
	Passive and active		P-A
Solar adaptation factors	Orientation		O
	Surface area/volume ratio		SA/V
	Arrangement		A
	Reflectivity		R
Source of inspiration	Name		–
	Adaptation means	Morphological	M
		Behavioural	B
		Morphological and behavioural	M-B
Materials and technologies-control mode	Static		S
	Responsive		R
	Responsive and dynamic		R-D
TRL [58]	Basic principles observed		1
	Technology concept formulated		2
	Experimental proof of concept		3
	Technology validated in lab environment/simulation		4
	Technology validated in relevant environment		5
	Technology demonstrated in relevant environment		6
	System prototype demonstration in operational environment		7
	Actual system completed and qualified through test and demonstration		8
	Actual system proven in operational environment		9

mixed methods and analyse the identified studies separately: (1) Qualitative studies focus on conceptual models and frameworks, these studies guide the discovery of relevant biological models and help evaluate their applicability to architectural problems. However, they often lack the empirical rigor required to validate solutions; (2) Quantitative studies employ computational modelling, simulations, and performance testing. These studies facilitate the testing and validation of design solutions; (3) Mixed-methods studies combine the strengths of both qualitative and quantitative approaches, providing a comprehensive solution from theory to application. This integration enables iterative feedback between qualitative insights and quantitative analysis, ensuring that the selected biological models are relevant and applicable, while also validating the design solutions through performance testing.

This study has identified in total 36 Bio-ASBE relevant outputs, where 14 studies use qualitative methods, 13 studies use quantitative methods, and 9 studies use mixed methods. The studies that employ qualitative methods were analysed against their adopted bottom-up or top-down approaches only and presented in Table 4. The studies that employ qualitative and mixed methods approaches were analysed against the rest of criteria from Table 3 and encapsulated in Table 5 for an overview.

Table 4
Existing qualitative studies on Bio-ASBEs.

Study number and reference	Contribution:	Approach: Top-down (Td) Bottom-up (Bu)
1 [6]	Presents a framework to provide a connection between building envelope design, plants' solar adaptation strategies, and building integrated photovoltaics It also identifies plant-inspired solar adaptation design factors	Td, Bu
2 [37]	Presents a bibliometric analysis and systematic review of smart materials for building envelopes followed by presenting a biomimetic design matrix	Td
3 [59]	Creates a link between Technology and biology for the development of biomimetic structures	Td Bu
[60]	Presents a classification of morphological solutions from nature for improving the buildings' performance	Bu
5 [61]	Proposes a set of classification criteria of biomimetic products and materials which are suitable for building envelope application	Bu
6 [62]	Proposes a bio-adaptive model (bio-AM) to achieve sustainable design solutions	Td
7 [14]	Proposes a kinetic façade design process capable of improving the thermal and visual comfort with a morphological approach	Td, Bu
8 [63]	Proposes a methodology that combines the AHP and TOPSIS techniques to evaluate and select the most effective nature-inspired approaches for designing climate-adaptive building shells.	Td, Bu
9 [64]	Advocates the promise of biomimetic methods for adaptive shading systems	Td
10 [65]	Evaluation of various types of shading systems to identify patterns and trends. Part of the study investigates the biomimetic design approach for hybrid shading systems	Td Bu
11 [66]	Represents the functional role of morphological adaptations in nature for their application in buildings	Bu
12 [67]	Part of this study explores the biomimetic approach to the design of dynamic shading systems	Td Bu
13 [36]	Providing a framework of nature's light managing strategies for building applications	Bu
14 [38]	Providing a framework of nature's heat regulation strategies for building envelope design	Bu

4.1.1. Qualitative methods

This section focuses on studies employing qualitative methods, including research presenting models, matrices, workflows, frameworks, patterns, identifications, and any other theoretical contributions within the field. Table 4 presents these studies' approaches including top-down and bottom-up and their contributions. For instance, in a study by Hosseini et al. [14] (Table 4, study 7), a theoretical framework is presented through interdisciplinary investigations for the development of a morphological approach for the kinetic façade design. Given its interdisciplinary nature, this study views the biomimetic approach as a blend of top-down and bottom-up approaches. Similarly, in a study by Jalali et al. [6] (Table 4, study 1), a bottom-up approach was used to identify solar adaptation factors in plants. Subsequently, employing a combination of top-down and bottom-up approaches, they introduced a framework linking plants' solar-responsive aspects to the properties of PV technologies. The objective was to advance the potential of integrating energy-generating PV technologies with biomimetic designs. In another study by Badarnah [38] (Table 4, study 14), a bottom-up approach is utilized to propose a biophysical framework for heat regulation, aiding in the design of building envelopes.

Analysing existing theoretical (qualitative) studies reveals that there is a lack of comprehensive design frameworks that address all aspects of solar adaptive strategies. While several studies offer valuable contributions to the field, they tend to focus on specific elements rather than providing a comprehensive integrated framework.

For instance [6], presents a framework connecting building envelope design with plant-inspired solar adaptation strategies and photovoltaics but does not extend beyond these aspects and is mainly focused on the solar harvesting feature. Similarly [62], proposes a bio-adaptive model with a broad approach concerning various environmental factors including water, temperature, wind, and sun. However, this model lacks a specific focus on solar adaptive solutions to delve deeper into this parameter. The kinetic façade design process in Ref. [14] highlight specific strategies like kinetic and dynamic mechanisms without integrating them into a broader bio-adaptive solar strategy framework.

Therefore, while each study offers significant insights, there remains a need for comprehensive frameworks that integrate various solar adaptive strategies to holistically address the challenges of solar management in building design.

4.1.2. Quantitative and mixed methods

This section focuses on studies employing quantitative or mixed (qualitative and quantitative) approaches, as presented in Table 5 and illustrated in Fig. 5 It demonstrates twenty-two Bio-ASBE applications through the development of concepts and case studies at various stages, using the analysis criteria outlined in section 4.1.

The studies explore the use of natural strategies to develop adaptive envelopes and systems through a biomimetic approach to harvest or/and regulate solar radiation and heat. For instance, Sommese et al. [68] (Table 5, study 1), developed a design concept for a kinetic system to improve daylighting and visual comfort. The design's solar strategy is solar regulation through shading inspired by the dynamic mechanism of *Gazania* flower. The morphology and movement behaviour of this plant have been the source of inspiration for this design and changes in the '*Surface area-to-volume ratio*' due to the panels' dynamic behaviour is this design's main solar adaptation factor according to the plant-inspired solar adaptation design factors identified by Jalali et al. [6]. They suggest that the light-responsive motion of the system could rely on the intrinsic properties of photosensitive polymers, but further studies are needed to physically test and validate the effectiveness of the prototype [68]. However, in another study by Badarnah [69]. (Table 5, study 22), '*Orientation*' has been the main solar adaptation design factor based on [6]. This is inspired by leaves changing their orientation to optimize light absorption, leading to the development of an external

Table 5
The analysis of Bio-ASBE studies, concepts and projects.

Number	Challenge	Solar strategy/ performance	Climate [70]	Adaptation mode	Context	Solar adaptation factor	Material and technology		methods	Source of inspiration		TRL
							Name	Control mode		name	Adaptation means	
1 [68]	DL, VC	S	C	P	It	S/V	photosensitive polymers	R D	M	Gazania Flower [Pl]	M B	4
2 [71]	TC	S	C	P	It	S/V	photochromic glazing SMA	R D	M	-Mimosa pudica -Cactus (Echinocatus grusonii) -Stone Plant (Lithops salicola) [Pl]	M B	4
3 [72]	EE,TC	S	NM	P	It	S/V	Adaptive shading device using TBM	R D	QN	Stomata Flowers [Pl]	M B	5
4 [73]	EE, TC	S	NM	P	It	S/V	Wood	R D	QN	Maranta leuconeura [Pl]	B	4
5 [55]	EE	Th	C	P	It	A	Biomimetic Radiative Cooling Glass	S	QN	Hercules beetle [An]	B	6
6 [74]	TC DL	S	B	NM	Ex	A O	bio-inspired interactive kinetic façade	R D	M	Stoma [Pl]	B	4
7 [75]	TC,EE	S	C	P	Ex	S/V	multifunctional Bio-ABS	R D	M	*Echinocactus grusonii*, a golden barrel cactus -stoma [Pl]	M B	4
8 [76]	TC,Aes	S	D	P	Ex	S/V	Adaptive shading system using climate-responsive wood bilayer actuators	R D	QN	Water Lily (Nymphaea) and the Purple Shamrock (Oxalis triangularis) [Pl]	M B	4
9 [77]	VC,DL	S	B	NM	Ex	A	multilayered biomimetic kinetic façade form	R D	QN	Tree [Pl]	M	4
10 [78]	IEQ,EE	Th	C A	P	NA	NA	-carbon nanotube aerogel -passive radiative cooler -thermochromic smart window -evaporative condensers	R	M	NA	NA	4
11 [79]	EH,EE	S, SH	D	A	Ex	O	mechanical responsive skin	R D	QN	Leaves [Pl]	B	3
12 [80]	EE	S	NM	P-A	NM	S/V	Eco-friendly building envelope	R D	M	Ice plant seed capsules [Pl]	B	4
13 [81]	EE	S	B	A	NM	S/V	Adaptive biomimetic façade	R D	QN	Oxalis oregana [Pl]	M B	4
14 [82]	NM	S	NM	A	NM	S/V	Flectofold—a biomimetic compliant shading device	R D	QN	Aldrovanda vesiculosa [Pl]	M B	4
15 [83]	EE	Th	NM	P	It	N/A	Building shell element called “cell”	S	QN	-Blubber -Brittle star surface [An]		3
16 [9]	DL	S	C	A	Ex	S/V	Kinetic Shading System	R D	QN	Lotus flower [Pl]	M B	4
17 [8]	EE	Th	D	P	Ex	R	biomimetic building envelope with a high albedo surface, and an integrated Bio-PCM and hydrogel system	S	QN	-African reed frog -the Hercules beetle [An]	B	4
18 [84]	NM	S	NM	P	NM	S/V	bio-inspired shading systems for double curved facades	R D	M	-*Strelitzia reginae*, -Aldrovanda vesiculosa -Lilium Casablanca [Pl]	M B	3
19 [85]	EE EH	SH S	C	A	Ex	S/V	“light” dynamic and adaptive façade system made from bioplastic and fibro elastic textiles	R D	QN	–	B	5
20 [86]	DL VC EE	S	NM	NM	Ex It	S/V	“Microloop” panels	R D	QN	seed pod of the American Sweetgum tree, Liquidambar Styraciflua [Pl]	B	3
21 [49]	EE TC	S Th	D/B	NM	It	S/V R	Bio-inspired Kinetic Envelope (BKE) system	R D	M	butterfly wings’ honeycombed microstructure [An]	B	3
22 [69]	EH EE	S SH	C	A	Ex	O	Energy generating and shading system	R D	M	Leaves [Pl]	B	3

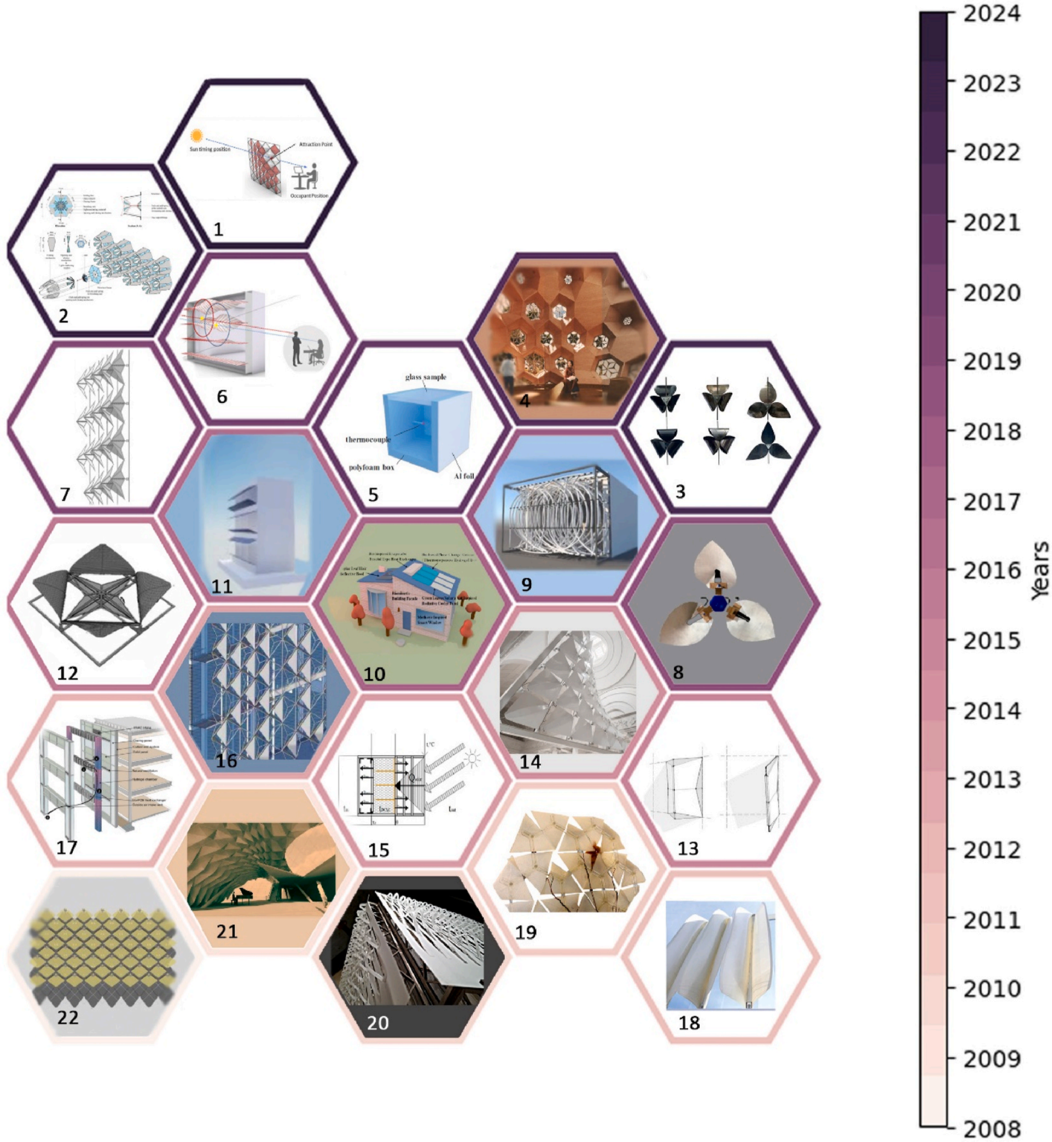

Fig. 5. Existing Bio-ASBE studies-concepts, over years (refer to Table 5 for corresponding study numbers, the order number is assigned chronologically). The colour gradient represents the chronological order from 2008 to 2022, with lighter shades indicating earlier years and darker shades reflecting more recent years. 1. Responsive kinetic façade system [68], 2. MBio-ABE, reprinted from Ref. [71] copyright (2024), with permission from Elsevier, 3. Adaptive shading device using TBM 4. Shading system [73], 5. Biomimetic Radiative Cooling Glass adapted from Ref. [55] copyright (2024), with permission from John Wiley and Sons, 6. Bio-inspired interactive kinetic façade [74] 7. Multifunctional Bio-ABS reprinted from Ref. [75] copyright (2024), with permission from Elsevier 8. Adaptive shading system [76], 9. Multilayered bio-inspired kinetic façade [77] 10. Bio-inspired building elements, reprinted from Ref. [78] copyright (2024), with permission from Elsevier 11. Mechanical responsive skin [79] 12. Adapted from Ref. [80] copyright (2024), with permission from Elsevier. 13. Adaptive biomimetic façade [81] 14. Flectofold [87] ITKE, University of Stuttgart, photographer: Kristie Meyer, 15. "cell" [83] 16. Kinetic shading system [9] 17. Adapted with permission from Ref. [8], published by Taylor & Francis Ltd [88]. Flectofin®shading façade system, reprinted from Ref. [47] copyright (2024), with permission from Elsevier, 19. Model prototype of dynamic skin [48], 20. Microloop panels [86], 21. Bio-inspired Kinetic Envelope (BKE) system [49], Image by Julian Wang, 22. Energy generating and shading system [69]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

energy-generating and shading system. Consequently, the challenge for this design is defined by the need to enhance both energy efficiency and energy harvesting [69].

4.2. Bibliometric analysis

A bibliometric analysis has been conducted according to the systematic searching approach set out in the methodology section using VOS viewer software. Each map is composed of nodes (or bubbles) linked by lines. The size of the nodes reflects their frequency of occurrence or citation, while the lines signify relationships between nodes, creating a visual network [89].

4.2.1. Themes and terminologies

Co-occurrence keyword graph provides a detailed visualization of the interconnected themes within the field of this research as demonstrated in Fig. 6. At the center of the graph, the keyword biomimetics stands out as the most prominent node, indicating its high frequency and central role within the dataset. Surrounding this central node are several distinct clusters of keywords, each represented by a different colour, signifying closely related sub-themes.

Five primary clusters emerge from the keywords as presented in Table 6. Cluster 1 – Responsive materials and systems; represents advancements in materials and systems that adapt to external stimuli. Keywords like smart materials, fabrication, bioprinting, and robotics

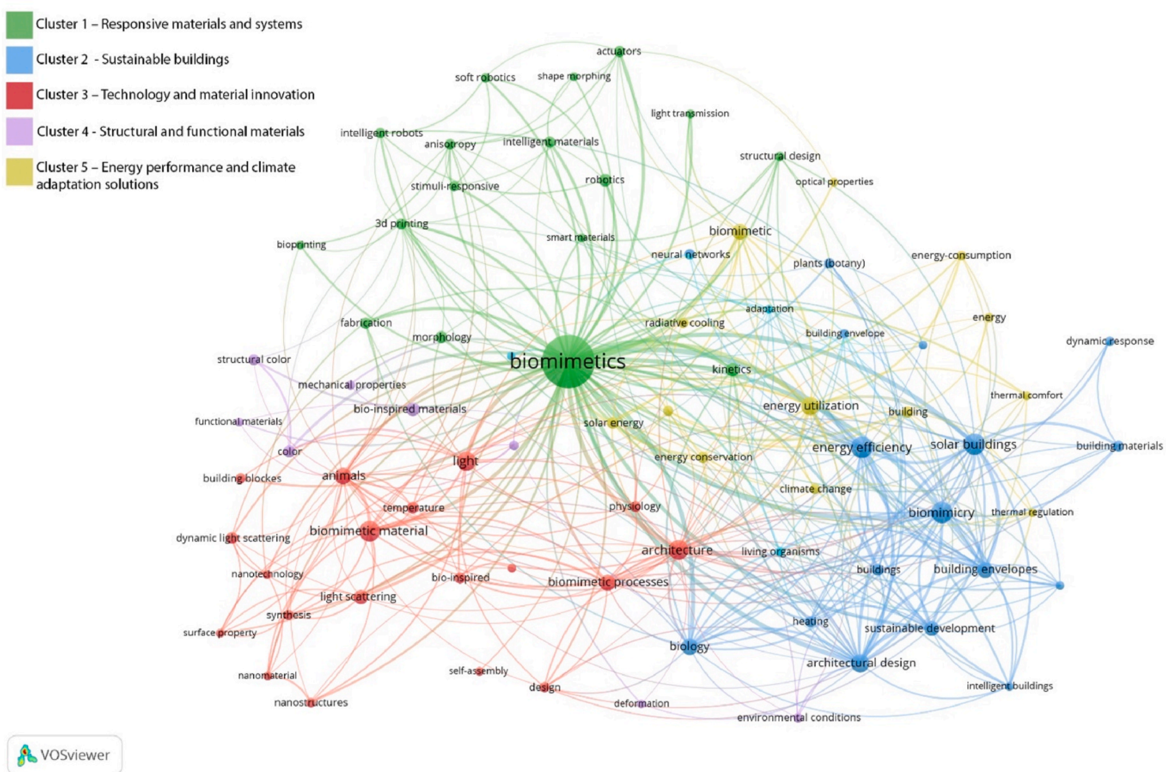

Fig. 6. Co-occurrence map of the keywords across five clusters: Cluster 1 – Responsive materials and systems, Cluster 2 – Sustainable buildings, Cluster 3 – Technology and material innovation, Cluster 4 – Structural and functional materials, Cluster 5 – Energy performance and climate adaptation solutions.

Table 6
Clusters of keywords.

Cluster 1 – Responsive materials and systems	biomimetics, smart materials, fabrication, bioprinting, 3d-printing, intelligent materials, Intelligent robots, kinetics, morphology, robotics, actuators, shape morphing, stimuli-responsive, light transmission, soft robotics, structural design, anisotropy
Cluster 2 – Sustainable buildings	biomimicry, energy efficiency, building materials, dynamic response, architectural design, sustainable development, building envelopes, buildings, intelligent buildings, plants, biology, computer simulation, heating, solar buildings, built environment,
Cluster 3 – Technology and material innovation	biomimetic material, temperature, animals, light, dynamic light scattering, nanotechnology, surface property, architecture, design, bio-inspired, self-assembly, biomimetic process, nanostructures, physiology, energy transfer,
Cluster 4 - Structural and functional materials	structural colour, mechanical properties, functional materials, colour, bio-inspired materials, biological materials, environmental condition, deformation
Cluster 5 – Energy performance and climate adaptation solutions	radiative cooling, biomimetic, energy utilization, solar energy, energy conservation, climate change, building, energy, energy consumption, thermal comfort, thermal regulation, optical properties, solar radiation

emphasize developments in dynamic, responsive technologies with applications in areas such as robotics, bioprinting, and shape morphing systems. Cluster 2 – Sustainable buildings; Focusing on biomimetic applications in architecture and sustainability, this cluster includes keywords such as energy efficiency, sustainable development, architectural design, and intelligent buildings. It reflects efforts to enhance energy conservation and adaptive building technologies inspired by natural principles. According to the graph, the building envelope is closely associated with enhancing responsiveness and intelligence, energy performance, and sustainable development. Cluster 3 – Technology and material innovation; encompassing nanotechnology, self-assembly, and bio-inspired design, this cluster highlights the role of cutting-edge technologies in creating biomimetic materials with novel surface and structural properties. Cluster 4 – Structural and functional materials; explores bio-inspired materials with unique mechanical properties and structural colour, emphasizing their functional applications in engineering and material sciences. Cluster 5 – Energy performance and climate adaptation solutions; with keywords like radiative cooling, solar energy, energy conservation, and thermal regulation underline focus on biomimetic approaches for enhancing energy efficiency and addressing climate adaptation challenges. These clusters collectively illustrate the interdisciplinary nature of biomimetics, connecting novel and responsive material and systems, architecture, technology, and sustainability to address complex challenges.

4.2.2. Evolving topics over years

An analysis also performed to explore how the topics shifted over time, between 2008 and 2024 which is shown in Fig. 7. The colour gradient reflects the temporal evolution of research topics, with purple signifying older research and yellow indicating recent advancements.

It shows that Cluster 1 – responsive materials and systems – has emerged as a new topic, with occurrences primarily concentrated in recent years. Notably, biomimetic, the most frequently occurring keyword, has gained prominence from 2020 onward. In addition, keywords such as soft robotics, shape morphing, actuators, 3D printing, have become more prevalent in recent studies. These terms highlight the growing integration of advanced technologies and techniques within the field. This shift underscores the increasing focus on dynamic, innovative design approaches, illustrating how technological advancements are shaping the future of bio-inspired design solutions. However, cluster 2 –

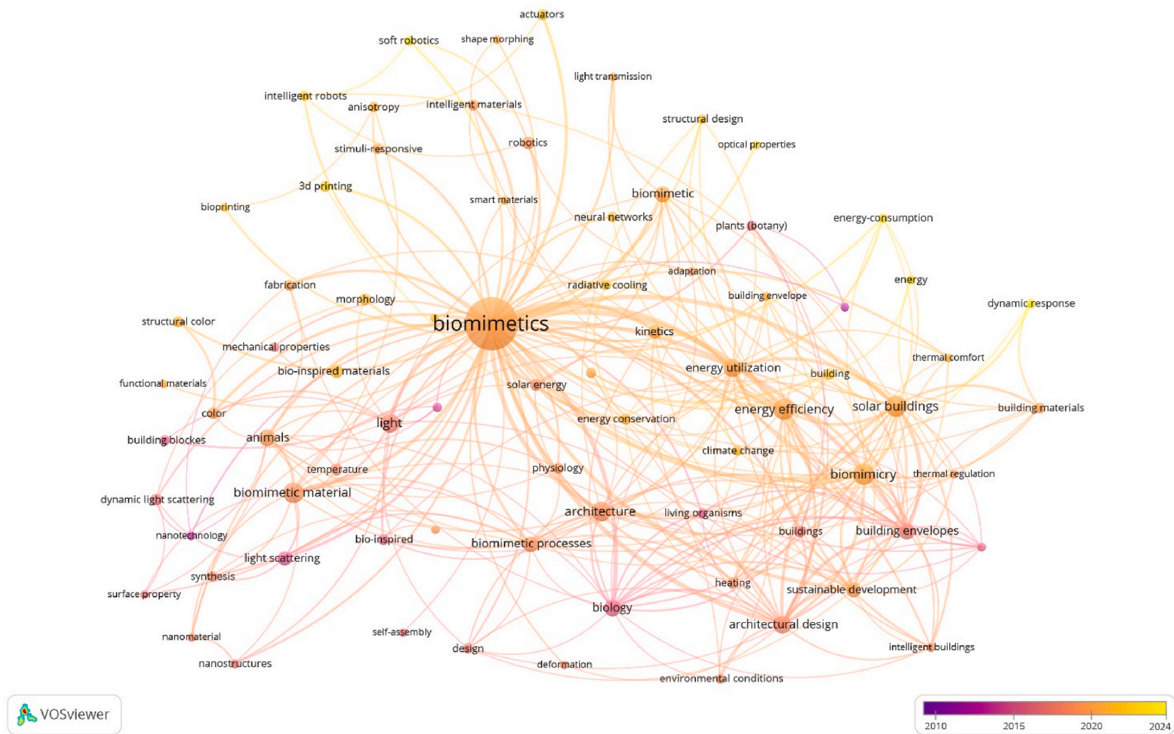

Fig. 7. Keywords co-occurrence of evolving topics across years.

Sustainable buildings, highlights a blend of both new and established research topics in building design, reflecting a shift towards more dynamic and responsive systems. Recent years show increased focus on adaptive technologies and sustainability, with terms like dynamic response, energy efficiency, and sustainable development gaining prominence, while building envelope and biology reflect established research areas.

Cluster 3 – Technology and Material Innovation, represents a blend of older foundational topics and newer emerging areas of research. Established keywords like nanotechnology, light, bio-inspired, light scattering, and self-assembly reflect the foundational technological advancements. While newer keywords such as biomimetic process, biomimetic material, architecture, and design highlight the evolving focus on applying nature-inspired principles to address design and

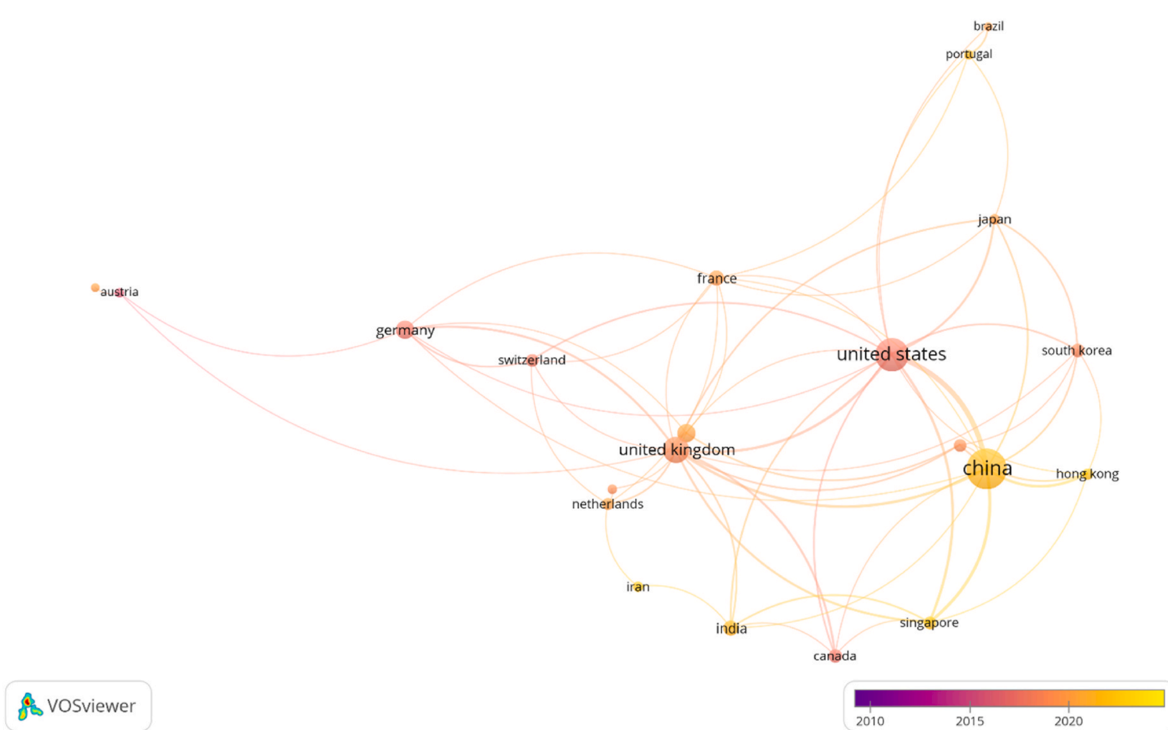

Fig. 8. Keywords collaboration patterns between countries across years.

architectural challenges. Cluster 4 represents the most recent advancements in the field, marked by keywords such as structural colour, functional materials, bio-inspired materials, and colour. These emerging topics underscore a focus on developing innovative materials that mimic biological systems, combining functionality with aesthetic appeal. Similarly, cluster 5, Energy performance and climate adaptation solutions, reflects new and evolving research themes, with terms like energy consumption and energy emerging as the most recent keywords in this cluster. Additionally, keywords such as building, thermal comfort, energy conservation, and climate change have gained prominence in the past few years.

4.2.3. Locations and collaborations

An analysis is performed using countries as the unit of analysis to examine co-authorship patterns as presented in Fig. 8. The minimum number of the documents of a country are set to 5. Thicker or more frequent connections indicate stronger research collaboration or co-citation frequencies. The colour gradient, from purple to yellow, represents a temporal dimension, where purple indicates earlier collaborations or activity and yellow represents more recent trends [89].

China's node size and yellow hue indicate a surge in research activity in the last decade, coupled with its expanding global influence. The United States also has a prominent node size and is extensively connected to other countries, emphasizing its dominant role in fostering international collaborations. European nations show strong intraregional cooperation, like among Germany, the United Kingdom, and France. Figure n demonstrate countries like India, Iran, Hong Kong, and Singapore are emerging hubs of recent research activity and their connections to other countries are growing.

These patterns emphasize the evolving dynamics of global research, highlighting both long-standing collaborations and the rise of new contributors shaping the future of scientific innovation.

The bibliometric analysis highlights the evolving nature of the field with emerging themes such as responsive materials, and advanced technologies like 3D-printing and soft robotics gaining prominence in recent years. The trends reveal a shift towards more dynamic and adaptable design solutions, reflecting growing interest in energy efficiency and climate adaptation. The analysis also suggests the recent appeal for nature-inspired approaches to address challenges in design and architecture. Additionally, global research activity is growing, with countries like China, the United States, the United Kingdom, and emerging hubs like India and Singapore playing key roles in advancing these trends [1]. The Bio-ASBE studies are introduced and analysed comparatively in this section to highlight the potential benefits, trends, and challenges associated with this topic. The data used for this analysis are collected as a result of the systematic review criteria set out in the methodology section.

4.3. Trends of Bio-ASBE studies

The trend of Bio-ASBE studies is investigated by analysing the number of studies over years. The line graph in Fig. 9 shows the number of studies conducted in this topic each year from 2008 to 2024. The number of studies from 2008 to 2012, remains low. A gradual increase begins; however, occasional sharp increases and decreases are observed afterward. The linear regression analysis shows a positive slope, indicating a slight upward trend in the number of studies conducted over the years from 2008 to 2024. The regression line (trendline) suggests that, despite the fluctuations, there is an overall increase in the number of studies.

4.4. Methods and approaches

Prevalence of studies based on their method is analysed across years to identify gaps and explore the potential of different approaches in the field. Fig. 10 indicates variability in the types of research conducted in this field, with the minority of research using mixed methods that combine both quantitative and qualitative approaches. This suggests a potential gap in the field and calls for more research that embraces mixed methods. The density of colours in the heatmap graph shown in Fig. 10 suggests that qualitative studies were more prevalent between 2015 and 2019, with a slight decrease thereafter. However, there appears to be a resurgence in qualitative studies in recent years, since 2022. Regarding quantitative studies, while they are prominent in certain years such as 2017 and 2022, their distribution is irregular, showing no continuous trend or pattern. Additionally, there are notable

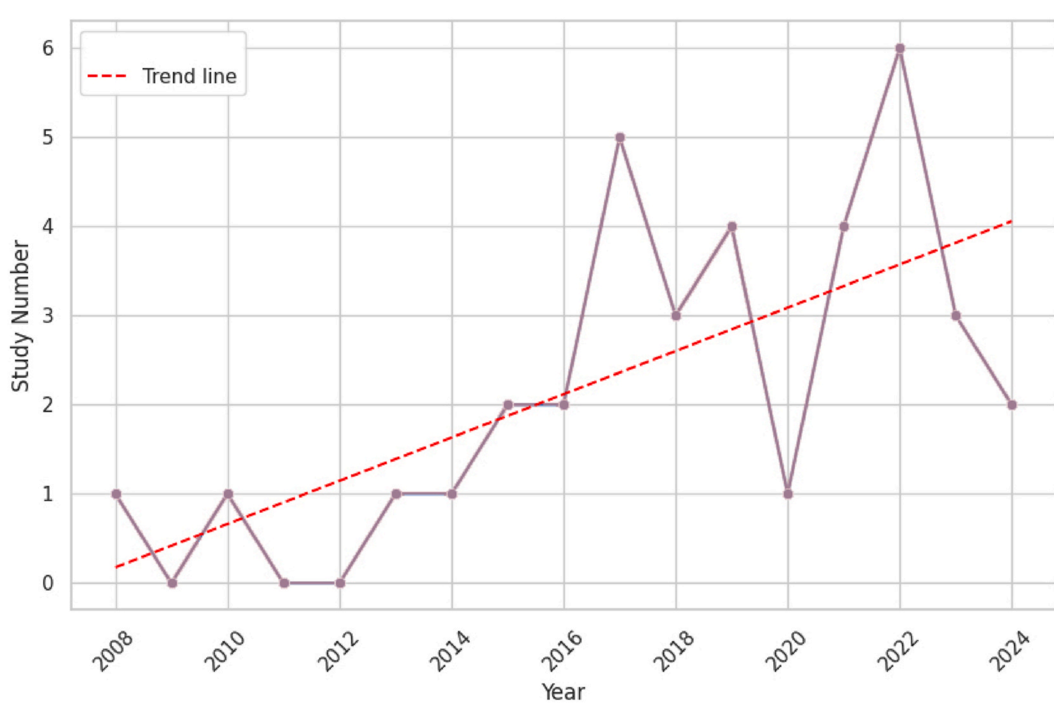

Fig. 9. Number of studies and trends in Bio-ABEs.

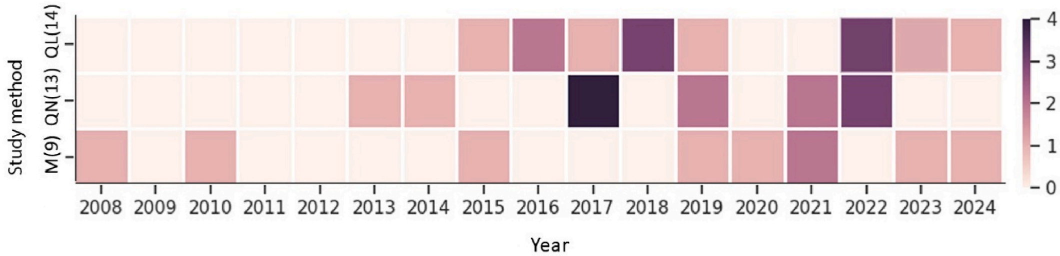

Fig. 10. The number of the studies based on their method over the years; the density of colours shows more frequency. Design challenges. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

gaps in research activity, with no quantitative studies conducted between 2008 and 2012, as well as in 2015, 2016, 2018, 2020, 2023, and 2024. In general, after 2016, there has been a growing interest in this topic, although it has experienced fluctuations.

Developing concepts and case studies through parametric modelling, numerical analysis, simulation, fabrication, and so forth leads to the evaluation of the applicability of the proposed solution in addressing the architectural challenge. Some studies [55] work on analysing/optimizing one challenge like energy efficiency (EE) and some work towards addressing multiple challenges like daylighting (DL) and thermal comfort (TC) [74], energy efficiency, and energy harvesting (EH) [85], visual comfort (VC), and daylighting [77] and other challenges listed in Table 5. While some studies have not clearly defined the challenge, a well-defined challenge eliminates the majority of irrelevant options in the exploration of the biological model, thereby increasing the efficiency of selecting suitable options. Additionally, it is essential for optimizing the design in terms of feasibility and preferred technology [38] as this approach provides the flexibility to select various factors within the challenge space.

Fig. 11 provides a visual representation of the number of studies addressing various challenges over the years from 2008 to 2024. The colour intensity represents the number of studies, with darker colours indicating a higher number of studies.

EE has received the most intense and consistent research focus, particularly peaking in 2019 and 2022. This trend reflects the global emphasis on reducing energy consumption and sustainability. Similarly, TC reached intense attention, particularly in 2021 and 2022, though less evenly distributed and frequent compared to EE. Both DL and VC exhibit consistent but less intensive and frequent research activity compared to EE and TC over the years, with more concentrations in recent years. Conversely, EH and Indoor environmental quality (IEQ) haven't received enough attention in recent years, underscoring the need for more studies, particularly in EH to promote energy-production practices. While aesthetics (Aes) is typically considered in design processes,

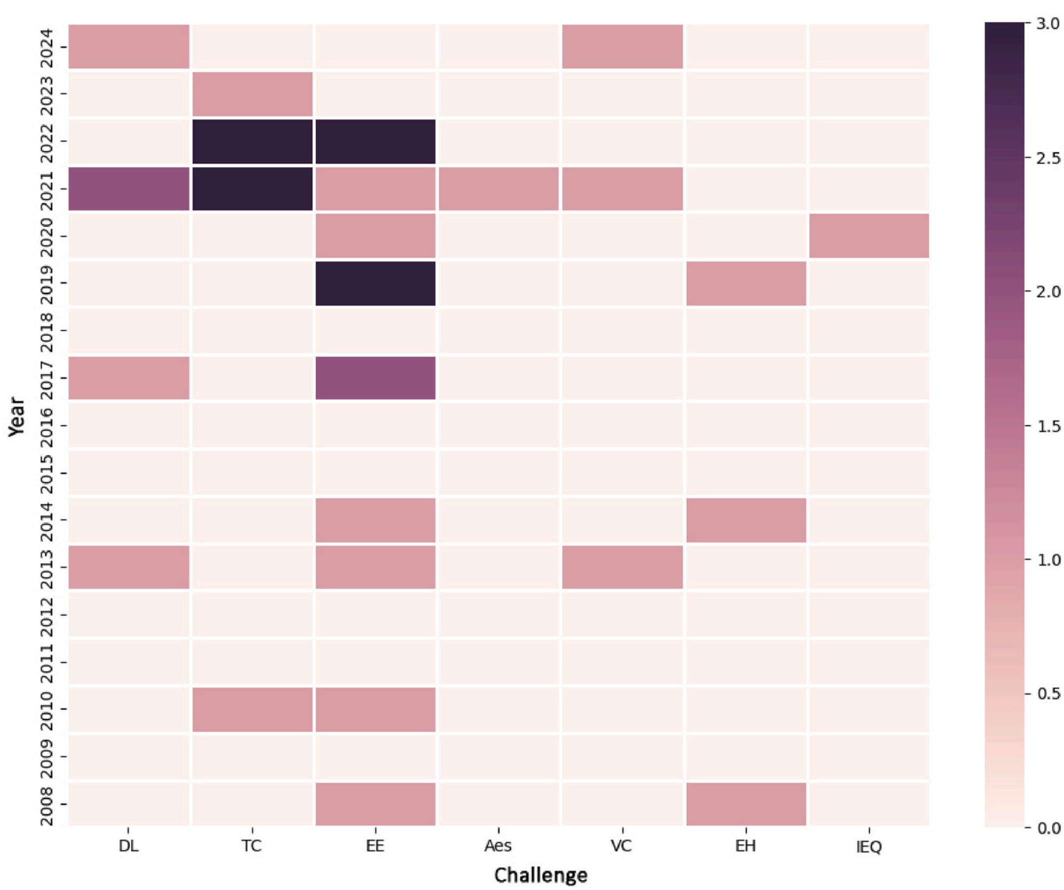

Fig. 11. Number of the studies over the years based on their challenge focus. The challenge focus includes daylighting (DL), thermal comfort (TC), energy efficiency (EE), aesthetical aspects (Aes), visual comfort (VC), energy harvesting (EH), and indoor environmental quality (IEQ).

they are often not explicitly mentioned in research, indicating a need for greater attention to this aspect.

The comparative analysis has been conducted across the studies on their solar performance, climate, adaptation mode, solar adaptation factors, source of inspiration, materials and technologies, and TRL. The data for the studies based on each of these categories are collected from Table 5. This analysis provides a structured understanding of the various parameters influencing biomimetic solar adaptive solutions, enabling the identification of potentials and areas requiring further development.

4.5. Performance

The Bio-ASBE solar adaptive strategies that identified in section 3 including solar regulation, solar harvesting and thermoregulation are analysed comparatively for the studies listed in Table 5. The studies adopting nature-inspired shading techniques fall under solar regulation, those employing solutions to capture solar energy fall under solar harvesting, and studies utilizing thermoregulation mechanisms, such as bio-inspired radiative cooling or reflectivity techniques, fall under the thermoregulation solar strategy.

The solar strategy distribution results shown in Fig. 12 demonstrate the overreliance on shading techniques and significant lack of studies adopting solar harvesting and thermoregulation strategies. The graph reveals a predominant emphasis on solar control and emphasizes the importance of developing integrated approaches that balance solar energy utilization with effective solar and heat regulation when necessary. Such approaches could ensure thermal comfort while mitigating overheating, addressing multiple challenges outlined in Section 4.4, for instance improving energy production, indoor environmental quality, and daylighting.

4.6. Climate

Natural organisms respond differently to various climatic conditions, developing strategies to prevent overheating in dry climates and adapting to capture more light in areas with low solar radiation. For example, flexible movements, such as changes in orientation and angle, allow plants to achieve optimal arrangements, maximizing or minimizing solar energy capture depending on climatic and environmental conditions [5,90]. Similarly, the significance of this factor should be considered in the design of building envelopes. The climate classes presented in Table 3 is based on Köppen-Geiger main classification [70] including tropical (A), arid (B), temperate (C), continental (D), and polar (E). The applicability and effectiveness of Bio ASBEs are closely linked to how each system's design is tailored to respond to different climatic condition. For example, in arid climates, external PV-integrated shading devices could help reduce solar heat gain while maximizing energy production. In colder climates (D and E), integrated systems that harvest and store solar energy internally might be more suitable, resulting in heat retention while still adapting to available light levels. Fig. 13 visualizes the number of studies addressing various solar strategies including solar regulation (shading), solar harvesting, and thermoregulation across different climates. It demonstrates that shading is studied more widely across different climate types particularly arid, temperate, and continental compared to other solar strategies. Additionally, a considerable number of studies have not mentioned their climatic focus. Moreover, solar harvesting strategies are underexplored compared to other approaches with only a single study in temperate climate. Given the high potential of solar harvesting, particularly in dry climates, the analysis highlights a critical area for further research. Additionally, the analysis underscores the need for more studies on thermoregulation and multifaceted solar strategies across diverse climate types.

4.7. Adaptation mode and context

Bio-ASBE can respond to solar radiation stimuli through active means, passive means, or a combination of both as classified in Table 3. The solar adaptive functions in buildings that require energy for activation or take place through circulatory systems are considered as active, while with passive strategies there is no need for using HVAC systems [91]. Loonen argues that passive and active systems are not mutually exclusive but can complement each other [92]. Regarding passive solar strategies, three key objectives have been identified for future facades: (I) maximizing light transmission, (II) selectively transmitting thermal solar radiation, and (III) selectively transmitting light. Achieving these targets offers numerous benefits, such as enhanced daylighting and visual comfort, reduced need for artificial lighting, and improved thermal comfort [2].

The studies' contexts are classified based on the positioning of the systems as presented in Table 3, whether they are internal, external, or integrated like the 'MBio-ABE' dynamic shading modules that are replaced by the window and integrated into the building envelope presented in Table 5, study 2 [71]. Typically, PV-integrated shading devices are situated externally to buildings [93]. This placement maximizes solar shading effectiveness by blocking sunlight before it enters the building. Furthermore, external positioning ensures optimal sunlight capture for electricity generation [6,93].

Fig. 14 depicts the adaptation mode of various systems over time, classified by their strategies (Passive, Active, Active and Passive, and Not Mentioned) and their contexts—positioning (Integrated, External, Not mentioned, and External and Integrated).

The box plot reveals that studies with the not mentioned label exhibit greater dispersity over the years compared to those with specified adaptation strategies (Passive, Active, Active-Passive). The whiskers extend across a wider range of years, indicating a broader distribution of

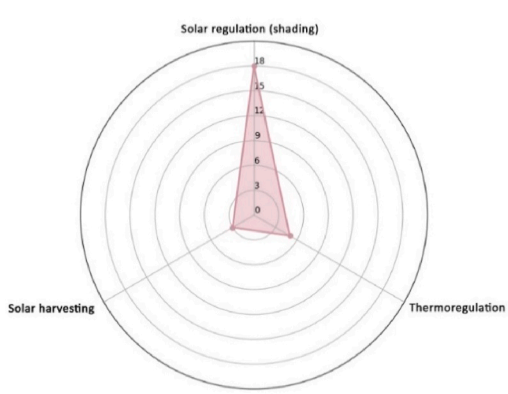

Fig. 12. Solar strategy distribution.

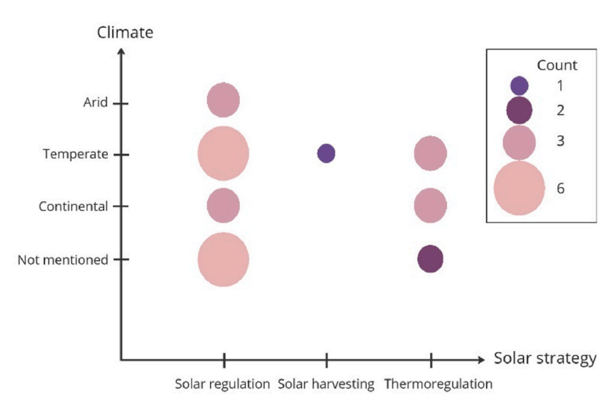

Fig. 13. Number of studies addressing the solar strategies including solar regulation, solar harvesting, and thermoregulation across different climates including tropical, arid, temperate, and continental. Studies lacking climate details are labelled as not mentioned.

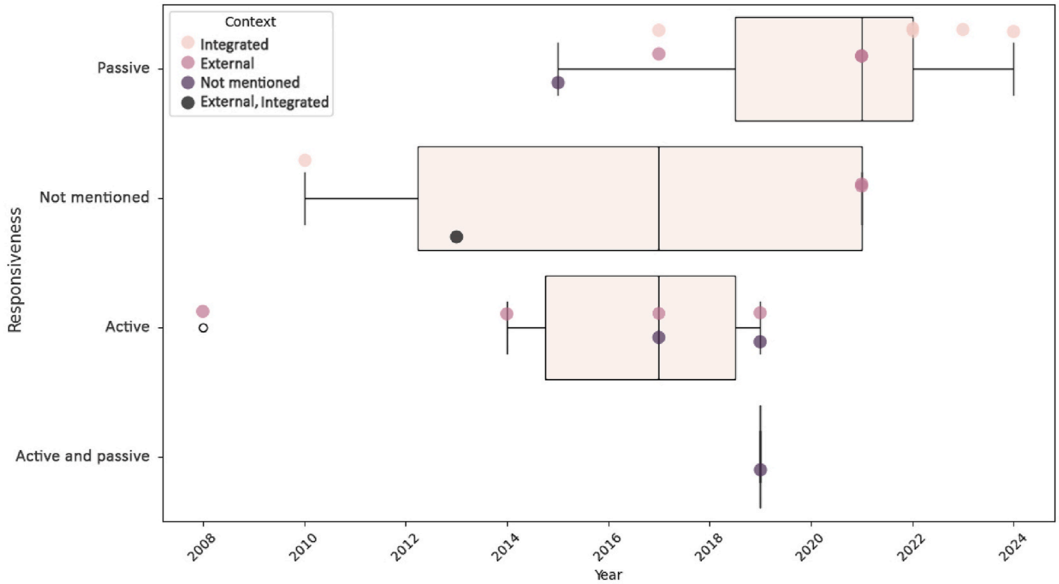

Fig. 14. Adaptation mode and context over years.

study years for the not mentioned category.

Studies adopting passives strategies show dispersity from 2015 to 2024, with some recent appearances. Conversely, the ones with active strategies are concentrated between 2014 and 2019, reflecting a focused period. The studies with active and passive strategies exhibit minimal dispersity, centered around 2019. Regarding context, Integrated positioning is mostly seen in passive systems, particularly in recent years, while active systems favor external positioning.

These findings highlight a growing interest in passive strategies and underscore the importance of clearly articulating the materials and systems' adaptation mode for future research for transparency and comparability across studies, aiding decision-making processes.

4.8. Solar adaptation factors

Taking inspiration from nature's strategies for managing sunlight, incorporating solar adaptation factors into the design of solar envelopes can enhance the effectiveness of Bio-ASBEs. Jalali et al. [6] have systematically categorized plants' adaptation features by observing their diverse strategies for coping with sunlight in various climates into four key solar adaptation factors: 'Orientation', 'Surface area to volume ratio', 'Arrangement', and 'Reflectivity'.

Systems with changeable angles and orientation fall under the category of 'Orientation'. In these systems, one approach is to design systems that track sunlight to capture energy and provide shading simultaneously [5,6,69,94,95]. Conversely, the case studies that utilize mechanisms such as fold, contact, and expand, and open and close fall under the category of changing 'Surface area to volume ratio' as one of the solar adaptation factors similar to plants' mechanisms for folding, curling, twisting, opening, and closing. 'Arrangement' can be considered on a large scale, focusing on the efficient placement of elements, or on a smaller scale, designing a single element or unit. Finally, the level of 'Reflectivity' whether low, high, or adjustable is another crucial solar adaptation factor. For instance, Fecheyr-Lippens and Bhiwapurkar [8] utilized high albedo materials to reflect solar radiation and adjusted indoor temperatures to achieve adaptive thermal comfort. They drew inspiration from the highly reflective body of the African reed frog, which aids the frog in surviving extreme heat conditions [8].

It is noteworthy that all these factors can vary and adapt dynamically over different timeframes, ranging from hours to seasons [6]. Furthermore, the combination of these factors can be employed in the design of Bio-ASBE.

The studies' frequencies are compared based on the solar adaptation factor they utilize, with their sources of inspiration within each category as demonstrated inFig.15. 'Surface area to volume ratio' has been the most frequently used solar adaptation factor in design followed by 'Orientation', 'Arrangement', and 'Reflectivity' respectively. Combinations of solar adaptation factors such as 'Arrangement-Orientation' and 'Surface area to volume ratio-Reflectivity' have been used in very few studies. Plants have been the most commonly used source of inspiration in the studies. Additionally, nearly all designs incorporating surface-to-volume and orientation factors have drawn from plant adaptations. This is likely due to plants' dynamic abilities to fold, curl, and twist to change their surface-to-volume ratio, as well as their light-tracking and self-shading behaviours relevant to the orientation factor by changing their leaf or stem angle.

4.9. Source of inspiration

Survival in nature depends on three key types of adaptations: physiological, morphological, and behavioural. Physiological adaptation involves an organism's response to external stimuli to maintain balance among interdependent elements. Morphological adaptations such as adjusting form (like twisted, curled leaves), pattern, and size refer to structural or geometrical features that enhance an organism's ability to adapt to environmental conditions. Behavioural adaptation refers to actions taken by organisms to ensure survival [5,31,39]. The source of inspiration for the case studies belongs to the kingdom of plants and animals as presented in Table 5. It shows that morphology and behaviour have informed most of the design solutions. Therefore, the case studies are categorized based on morphological means, behavioural means, and a combination of both. For instance, in the study by Sheikh and Asghar [81], the shading module's basic shape is inspired by the leaf's physical structure (morphological adaptation), while its functionality is drawn from leaf angles' adjustment based on light intensity and detecting and tracking the sun's movements to optimize exposure (behavioural adaptation) [81] (Table 5, study 13).

Fig. 15 also suggests that while plants, animals, and other categories of natural kingdom offer valuable lessons for bio-inspired design, the adaptations seen in plants tend to be more commonly utilized in architectural applications. This is likely because plants exhibit dynamic adaptive strategies that can be implemented in static structures.

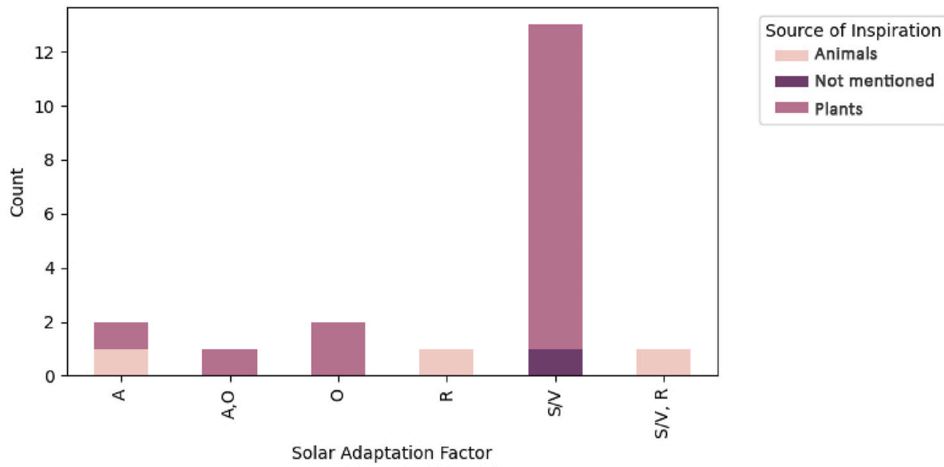

Fig. 15. Frequency of the studies based on solar adaption factor and source of inspiration; the Solar adaptation factors include Orientation(O), Surface area to volume ratio (S/V), Arrangement (A), and Reflectivity (R).

Furthermore, the bar plot in Fig. 16 provides a visual comparison of the number of studies that draw inspiration from different types of adaptation strategies in nature presented as adaptation means in Table 3 and consists behavioural (B), a combination of morphological and behavioural (M − B), and solely morphological (M) categories.

The data indicates that studies incorporating behavioural (B) and combined morphological and behavioural (M − B) strategies are more prevalent than those focusing exclusively on morphological (M) strategies. Specifically, the count for behavioural strategies (B) is the highest, followed by the combination of morphological and behavioural strategies (M − B), with morphological strategies (M) being the least common. This trend suggests that the field of biomimetics is evolving beyond merely using nature as a source of formal morphological concepts. Instead, it highlights an increasing recognition of the importance of behavioural strategies and their integration with morphological insights.

4.10. Materials and technologies

Some of the selected studies presented in Table 5 propose new bio-inspired technological systems. For example, Vanaga et al. [83] proposed a *'climate-adaptive building shell element'*—a cell designed to accumulate and release solar energy to the internal space [83]. On the other hand, other studies utilize existing technologies or materials to develop bio-inspired glazing or façade. For instance, Kuru et al. [75] developed and analysed the performance of 'Multi-functional Bio-ABS' which offers shading through photovoltachromic (PVC) glazing and ventilation through openings activated by Shape Memory Alloy (SMA) springs [75]. Smart materials are among the new efficient technologies that are able to achieve variant reversible shapes triggered by different stimuli like electricity and heat. Consequently, actuating and sensing functions could be integrated into the building envelope elements [67,96] making the building envelope responsive in a way that either provides shadow or instead let in the sunlight when required [4].

The control modes of materials and technologies are classified as static, responsive, and responsive-dynamic, based on insights from the literature outlined in Table 2. Fig. 17 illustrates that Bio-ASBE studies predominantly adopt responsive and dynamic materials and technologies, which aligns with the inherent characteristics of biological systems that often involve adaptability and movement. Future research should build on this trend by further advancing the development of dynamic and responsive systems and materials.

4.11. TRL

Technology Readiness Levels (TRLs) are a standardized way to measure how mature a technology is, and they allow for consistent and uniform discussions about the maturity of different technologies.

In this research, TRL is used as a measurement tool to conduct a

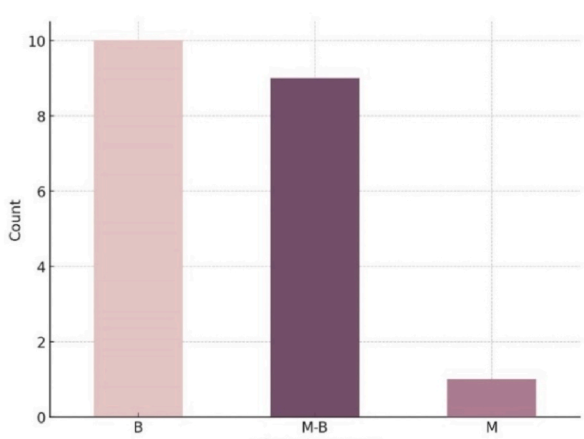

Fig. 16. Number of studies based on type of their solar adaptation means. Adaptation means include Behavioural (B), Morphological (M), Morphological and Behavioral (M–B).

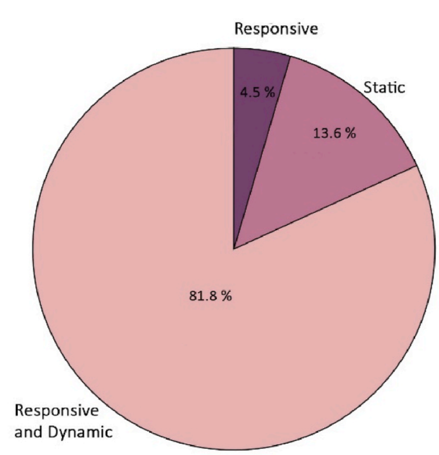

Fig. 17. Materials and technologies' control modes including static, responsive, and responsive and dynamic.

comparative analysis across the quantitative and mixed studies listed in Table 5 and assess their readiness levels (1–9) as over the years. Since the selected studies are not purely theoretical and involve developing case studies, the minimum level considered is Proof-of-Concept Demonstrated (level 3). Studies that conducted comprehensive simulations and analyses using real weather data and assessed the design in a lab-like environment, are classified as Laboratory Validated (level 4). Studies that meet more advanced criteria are assigned higher levels. In this research, TRL is assessed across all Bio-ASBE studies to highlight trends and gaps in the field. Specific TRL assignment for each study is presented in Table 5.

Fig. 18 illustrates the progression of research activity from 2008 to early 2024, with the x-axis representing the years and the y-axis indicating the TRLs. The individual points on the plot represent the TRLs assigned to each study. A regression line highlights an upward trend, indicating that research activities have increasingly moved towards higher TRLs over time. This trend suggests that the technologies studied have generally advanced from early-stage concepts to more developed and potentially deployable technologies.

5. Discussions: challenges, opportunities and future pathways

Drawing insights from nature can inform a wide range of architectural considerations, from the form and structure of buildings—such as livMatS Biomimetic Shell which is inspired by the morphological aspects of the plate skeleton of sea urchins which allowed for reusability and separability of the structural components [97] to the development of new materials, like biomimetic hygro-actuated wooden building systems that offers energy-saving through weather adaptive movement and self-shaping mechanisms [98]. Additionally, nature-inspired strategies can enhance both passive and active systems, such as adaptive shading and energy-generating panels, composite actuator [99] and smart robotic elements [100] that could lead to improved energy performance by mimicking natural insulation properties, cooling mechanisms, and solutions for overheating, while enhancing daylighting and promoting occupant thermal comfort, visual comfort, and therefore overall well-being of the user.

This research provides a classification of biomimetic adaptive solar design solutions including solar regulating, solar harvesting, and thermoregulation which could provide valuable insights for responsive design advancements.

This research shows that there is an upward trend in the number of studies conducted, which likely reflects a combination of drivers. The gradual increase in publications from 2013 onward could correspond to the growing global focus on sustainable architecture and adaptive technologies, driven by the pressing challenges of climate change. Academic advancements, such as innovations in computational modelling tools and breakthroughs in new materials such as shape-morphing material, have also likely played a pivotal role in fuelling research activity. The low number of studies in 2020 could be due to the fact that this research only screened publications indexed in Scopus, which may not capture all relevant studies. Additionally, the COVID-19 pandemic could have impacted research productivity during that time. The low number of studies in 2024 is because the analysis was conducted early in the year, meaning it does not reflect the full range of publications that released later in the year. Looking forward, the field is expected to grow further, driven by emerging technologies such as material programming, 4D printing, advanced robotics, fabrication and manufacturing techniques like additive manufacturing, and the integration of Artificial Intelligence.

These advancements promise to unlock new possibilities for adaptive and responsive systems, potentially transforming the architectural landscape and enabling the development of highly efficient, nature-inspired designs. Despite sporadic progress, the limitations in integrating diverse strategies, addressing multifaceted challenges, and achieving practical applicability suggest that the field is still maturing. More advancements and efficiency in the field can be achieved through multifunctional solutions where different functions integrated in a single element [67]. For instance, building envelopes integrated shading devices that can provide energy generation as well as solar regulation through adaptive shading for the buildings. Many studies prioritize isolated aspects, such as kinetic mechanisms or energy efficiency, often neglecting the interplay between multiple factors like thermal comfort, energy harvesting, and daylighting. This gap makes it challenging to translate the generated concepts into comprehensive, adaptable, and scalable design solutions.

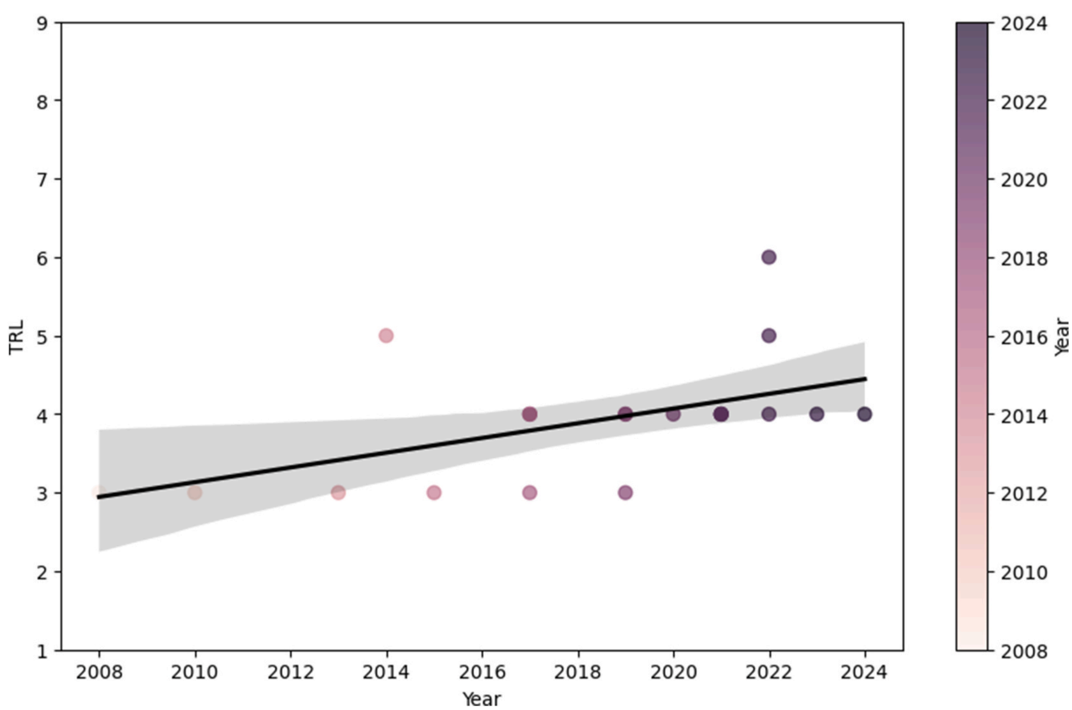

Fig. 18. TRL trend over years.

The limited scalability of current studies is further underscored by the relatively low TRLs observed across the field. While there is a discernible trend toward higher TRLs, the majority of studies remain in early-stage development, with limited real-world validation. This disconnects between conceptual innovation and practical application hinders the broader adoption and integration of Bio-ASBEs into mainstream architectural practices. Furthermore, the predominance of theoretical explorations, especially in qualitative studies, has not been matched by the development of practical models that can address real-world complexities. Similarly, while quantitative studies have contributed valuable data, they have yet to translate into concrete, applicable solutions for practical implementation. Therefore, there is a need for more studies that employ mixed approach. These types of studies can provide a more comprehensive understanding of research problems by leveraging the strengths of both qualitative and quantitative approaches. For instance, while quantitative data can offer insights into concept development and application, qualitative data can provide depth and contextual insights. By integrating these approaches, mixed methods research can bridge the gap between theoretical methods and practical applications, leading to more nuanced and robust findings.

Moreover, reflecting on the theoretical investigations, this research highlights the need for comprehensive frameworks that integrate various solar adaptive strategies. While individual studies have made valuable contributions, they often focus on isolated elements such as energy efficiency or daylighting without providing a holistic approach to solar adaptation. To address this gap, future research should prioritize the development of integrated frameworks that combine multiple adaptive strategies, recognizing the complex and multifaceted nature of solar management in building design.

The data analysis also reveals fluctuating trends in the focus of research challenges over time. Energy efficiency have received consistent attention, and thermal comfort have received a relatively high attention in the past years reflecting their critical importance in sustainable building design. However, other challenges such as energy harvesting and indoor environmental quality have not garnered as much focus in recent years, highlighting gaps in the field. As buildings increasingly integrate renewable energy sources and aim for energy-positive outcomes, the role of energy harvesting in adaptive building envelopes should be given more attention particularly in terms of developing practical, scalable systems that can integrate seamlessly with existing architectural structures.

Limitation of this review lies in the focus on Scopus-indexed papers. Future systematic reviews could expand to include other databases, such as Web of Science, to capture a broader range of literature. Additionally, incorporating ongoing or unpublished Bio-ASBE projects could provide a better understanding of their current TRL state, leading to more real-world applications.

6. Conclusions

Sustainable and renewable energy resources are becoming more and more important, while the energy demand worldwide increases. In this context, the building envelope's role to harvest or regulate solar energy as one of the natural and renewable energy resources is recognized. This research focuses on the interdisciplinary realm encompassing Adaptive Building Envelopes, Solar Adaptation Strategies, and Biomimetics and explores the potential of inspiration from nature in solar management by integrating it into the building envelope for a more efficient design. It presents a classification of biomimetic solar management strategies, which encompasses solar regulation (shading), solar harvesting, and thermoregulation. This research also conducts a comparative analysis of relevant publications. By systematically examining studies focused on biomimetic adaptive building envelopes (Bio-ASBEs), it highlights trends, gaps, and opportunities in the field.

First and foremost, our findings reveal an upward trend in interest since 2013, representing a growing recognition of the applicability and efficacy of biomimetic approaches in addressing the challenges associated with solar management in buildings. This trend represents the evolving nature of this field, as studies increasingly embrace innovative solutions inspired by nature's solar adaptation design principles. However, the analysis uncovers a gap in research methods. While quantitative and qualitative studies are exclusively abundant, there is a lack of mixed-methods, which combines both qualitative and quantitative approaches. Therefore, the results highlight the necessity of a shift towards more comprehensive and multifaceted studies that integrate theory and application as a critical means of developing a more in-depth understanding of the potential of Bio-ASBEs and their role in achieving sustainable buildings.

Furthermore, the result of this study reveals a predominant reliance on single solar strategy like shading techniques. While undeniably effective, this narrow focus may overlook other promising alternative strategies available, each offering unique advantages in improving the building's solar management performance. Also, by integrating two or multiple solar strategies more comprehensive and synergistic solutions can be achieved.

Finally, the review underscores the potential of expanding the realm of inspirational sources beyond plants exclusively. While plant adaptations offer invaluable insights, other realms of the natural world provide unique strategies that could enrich biomimetic design endeavours. Future development of Bio-ASBEs could benefit significantly from advancements in new materials, intelligent control systems, photovoltaic technologies, and advanced computational and fabrication techniques. For instance, emerging materials with adaptive, passive, and responsive properties could enable Bio-ASBEs to respond in real time to environmental changes, enhancing their performance. The incorporation of systems, actuators, and materials that allow Bio-ASBEs to optimize functions dynamically, adjusting solar regulation, harvesting and thermoregulation based on data inputs to maximize energy production, control glare, improve daylight, and enhance occupant comfort and well-being is recommended. Including user input into these systems could further fine-tune performance, making them even more adaptable and responsive to occupants' needs. Furthermore, this review is limited to Scopus-indexed papers. Future studies could include other databases and unpublished Bio-ASBE projects to better assess TRL and real-world applications.

The practical application of Bio-ASBEs can draw valuable insights from theoretical models, frameworks, and biological databases but also requires dedicated research and development to translate biological principles into architectural solutions that meet real-world challenges. Due to the inherent flexibility needed in aspects such as form, scale, mechanics, and materials, the initial costs of these systems may be higher than those of traditional building systems. However, these systems hold significant potential for long-term advantages, offering improvements in cost-effectiveness, sustainability, and energy performance over time.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] Luther M, Altomonte S. Natural and environmentally responsive building envelopes. 37th international conference on environmental systems (ICES), Chicago, Illinois, July 9-12, 2007. Society of Automotive Engineers; 2007. p. 1–12.
[2] Gosztonyi S, Brychta M, Gruber P. Challenging the engineering view: comparative analysis of technological and biological functions targeting energy efficient facade systems, vol. 138. WIT Transactions on Ecology and the Environment; 2010. p. 491–502.
[3] Lenau TA, Lakhtakia A. Biologically inspired design: a primer. Synthesis lectures on engineering. Sci Technol 2021;3:1–115.
[4] Jalali S, Aliabadi M, Mahdavinejad M. Learning from plants: a new framework to approach water-harvesting design concepts. Int J Build Pathol Adapt 2021. https://doi.org/10.1108/IJBPA-01-2021-0007. ahead-of-p.
[5] Jalali S, Davies A, Badarnah L, Nicoletti E. Design lessons from plant for adaptive solar skins. SEEDS conference 2022. Bristol, United Kingdom: International Conference for Sustainable Ecological Engineering Design for Society); 2022.
[6] Jalali S, Nicoletti E, Badarnah L. From flora to solar adaptive facades: integrating plant-inspired design with photovoltaic technologies. Sustainability 2024;16:1145.
[7] Anghel AA, Mohora I, Frigura-Iliasa FM, Giurea D, Preda A-D, Milincu C. Smart responsive green walls for public transportation areas in Timisoara. 2019 IEEE international conference on environment and electrical engineering and 2019 IEEE Industrial and Commercial power systems Europe (EEEIC/I&CPS Europe). 2019. p. 1–4. IEEE.
[8] Fecheyr-Lippens D, Bhiwapurkar P. Applying biomimicry to design building envelopes that lower energy consumption in a hot-humid climate. Archit Sci Rev 2017;60:360–70.
[9] Jahanara A, Fioravanti A. Kinetic shading system as A means for optimizing energy load. SharingofComputableKnowledge 2017:231.
[10] Lenau T, Ahmad F, Lakhtakia A. Towards biomimetic red solar cells. Bioinspir. Biomimet. Bioreplicat. 2019;10965:83–96. SPIE.
[11] Bläsi B, Kroyer T, Kuhn TE, Höhn O. The MorphoColor concept for colored photovoltaic modules. IEEE J Photovoltaics 2021;11:1305–11.
[12] Halme J, Mäkinen P. Theoretical efficiency limits of ideal coloured opaque photovoltaics. Energy Environ Sci 2019;12:1274–85.
[13] Antonini E, Boeri A, Giglio F. Classification criteria and markers for biomimetic building envelope within circular economy principles: a critical review. Architect Eng Des Manag 2021:1–23.
[14] Hosseini SM, Mohammadi M, Rosemann A, Schröder T, Lichtenberg J. A morphological approach for kinetic façade design process to improve visual and thermal comfort. Build Environ 2019;153:186–204.
[15] Grant MJ, Booth A. A typology of reviews: an analysis of 14 review types and associated methodologies. Health Inf Libr J 2009;26:91–108.
[16] https://www.vosviewer.com/n.d.
[17] Vattam SS, Goel AK. Foraging for inspiration: understanding and supporting the online information seeking practices of biologically inspired designers. In: International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. 54860; 2011. p. 177–86.
[18] Bradshaw V. Building control systems. Wiley; 1993.
[19] Knaack U, Klein T, Bilow M, Auer T. Façades: principles of ConstructionSecond and Revised Edition. Birkhäuser; 2014. https://doi.org/10.1515/9783038211457.
[20] Tabadkani A, Roetzel A, Li HX, Tsangrassoulis A. Design approaches and typologies of adaptive facades: a review. Autom ConStruct 2021;121:103450.
[21] Hubert T, Dugué A, Vogt Wu T, Aujard F, Bruneau D. An adaptive building skin concept resulting from a new bioinspiration process: design, prototyping, and characterization. Energies 2022;15. https://doi.org/10.3390/en15030891.
[22] Kim H, Clayton MJ. A multi-objective optimization approach for climate-adaptive building envelope design using parametric behavior maps. Build Environ 2020; 185:107292. https://doi.org/10.1016/j.buildenv.2020.107292.
[23] Parsaee M, Demers CM, Hebert M, Lalonde J-F, Potvin A. Biophilic, photobiological and energy-efficient design framework of adaptive building façades for Northern Canada. Indoor Built Environ 2021;30:665–91.
[24] Attia S. Adaptive facades performance assessment, interviews with facade experts. 2019.
[25] Klysner NF, Lenau TA, Lakhtakia A. Building-integrated photo-voltaics: market challenges and bioinspired solutions. Bioinspirat. Biomimet. Bioreplicat. 2021; 11586:32–47. SPIE.
[26] Sung DK. Skin deep: breathing life into the layer between man and nature, vol. 3. AIA Report on University Research; 2008.
[27] Lopez M, Rubio R, Martín S, Croxford B, Jackson R. Adaptive architectural envelopes for temperature, humidity, carbon dioxide and light control. 10th conference on advanced building skins. 2015. Bern, Switzerland.
[28] Sun L, Huang WM, Ding Z, Zhao Y, Wang CC, Purnawali H, et al. Stimulus-responsive shape memory materials: a review. Mater Des 2012;33:577–640.
[29] Granqvist CG. Electrochromics and thermochromics: towards a new paradigm for energy efficient buildings. Mater Today Proc 2016;3:S2–11.
[30] Kenisarin M, Mahkamov K. Passive thermal control in residential buildings using phase change materials. Renew Sustain Energy Rev 2016;55:371–98.
[31] Al-Obaidi KM, Ismail MA, Hussein H, Rahman AMA. Biomimetic building skins: an adaptive approach. Renew Sustain Energy Rev 2017;79:1472–91.
[32] Khoo CK, Salim FD. Lumina: a soft kinetic material for morphing architectural skins and organic user interfaces. Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing. 2013. p. 53–62.
[33] Jochum FD, Theato P. Temperature-and light-responsive smart polymer materials. Chem Soc Rev 2013;42:7468–83.
[34] Wu LYL, Zhao Q, Huang H, Lim RJ. Sol-gel based photochromic coating for solar responsive smart window. Surf Coat Technol 2017;320:601–7.
[35] Benyus JM. Biomimicry: innovation inspired by nature. 1997.
[36] Badarnah L. Light management lessons from nature for building applications. Procedia Eng 2016;145:595–602.
[37] Sommese F, Badarnah L, Ausiello G. Smart materials for biomimetic building envelopes: current trends and potential applications. Renew Sustain Energy Rev 2023;188:113847.
[38] Badarnah L. A biophysical framework of heat regulation strategies for the design of biomimetic building envelopes. Procedia Eng 2015;118:1225–35.
[39] Vattam S, Helms ME, Goel AK. Biologically-inspired innovation in engineering design: a cognitive study. Georgia Institute of Technology; 2007.
[41] Conservation Magazine. Homeostatic building façade n.d. https://www.anthropocenemagazine.org/conservation/2013/03/homeostatic-building-facade/?gad_source=1&gclid=Cj0KCQiA1p28BhCBARIsADP9HrO7pK2b0zXZMVvrgy7-nVezUEWqVIHXJZOVZbQTwAA01P3tYfrVbeAaAq1SEALw_wcB. [Accessed 15 January 2025].
[42] Lift Architects. THE AIR FLOW(ER) n.d. https://www.liftarchitects.com/#/air-flower.(accessed January 15, 2025).
[43] Menges A, David Krieg O, Reichert S. HygroSkin: Meteorosensitive Pavilion n.d.
[44] Cheng T, Tahouni Y, Sahin ES, Ulrich K, Lajewski S, Bonten C, et al. Weather-responsive adaptive shading through biobased and bioinspired hygromorphic 4D-printing. Nat Commun 2024;15:1–13.
[45] Institute for Computational Design and Construction. HygroSkin: Meteorosensitive Pavilion n.d. https://www.icd.uni-stuttgart.de/projects/hygroskin-meteorosensitive-pavilion/(accessed January 15, 2025).
[46] Institute for Computational Design and Construction. Solar Gate n.d. https://www.icd.uni-stuttgart.de/projects/solar-gate/. [Accessed 15 January 2025].
[47] Esteso-Martínez J, Valladares F, Camarero JJ, Gil-Pelegrín E. Crown architecture and leaf habit are associated with intrinsically different light-harvesting efficiencies in Quercus seedlings from contrasting environments. Ann For Sci 2006; 63:511–8.
[48] van der Kooi CJ, Elzenga JTM, Dijksterhuis J, Stavenga DG. Functional optics of glossy buttercup flowers. J R Soc Interface 2017;14:20160933.
[49] Wang J, Li J. Bio-inspired kinetic envelopes for building energy efficiency based on parametric design of building information modeling. 2010 Asia-Pacific power and energy engineering conference. IEEE; 2010. p. 1–4.
[50] Ehleringer JR, Björkman O. Pubescence and leaf spectral characteristics in a desert shrub, Encelia farinosa. Oecologia 1978;36:151–62.
[51] Azizian D, Moore DM. Morphological and palynological studies in Phlomis L., Eremostachys Bunge and Paraphlomis Prain (Labiatae). Bot J Linn Soc 1982;85: 225–48.
[52] Land MF. The optics of animal eyes. Contemp Phys 1988;29:435–55.
[53] Sun J, Bhushan B, Tong J. Structural coloration in nature. RSC Adv 2013;3: 14862–89.
[54] Jalali S, Costa E, Barakat M, Badarnah L. Color-changing envelope: a biomimetic approach for designing an environmentally responsive shelter. 2024.
[55] Zhang X, Li X, Wang F, Yuan W, Cheng Z, Liang H, et al. Low-cost and large-scale producible biomimetic radiative cooling glass with multiband radiative regulation performance. Adv Opt Mater 2022;10:2202031.
[56] Ye C, Li M, Hu J, Cheng Q, Jiang L, Song Y. Highly reflective superhydrophobic white coating inspired by poplar leaf hairs toward an effective "cool roof.". Energy Environ Sci 2011;4:3364–7.
[57] Kobelt F, Linsenmair KE. Adaptations of the reed frog Hyperolius viridiflavus (Amphibia, Anura, Hyperoliidae) to its arid environment. Oecologia 1986;68: 533–41.
[58] Mankins JC. Technology readiness levels. White Paper, April 1995;vol. 6:1995.
[59] Dikou C. Sustainability, through passive solar building envelope design, based on the principles of bioinspiration. In: E3S Web of Conferences. 436; 2023. p. 1013. EDP Sciences.
[60] Badarnah L, Zolotovsky K. Chapter 15 - morphological differentiation for the environmental adaptation of biomimetic buildings: skins, surfaces, and structures. In: Eggermont M, Shyam V, editors. Hepp design and Habitats AFBT-B for M. Elsevier; 2022. p. 439–66. https://doi.org/10.1016/B978-0-12-821053-6.00007-2.
[61] Antonini E, Boeri A, Giglio F. Classification criteria and markers for biomimetic building envelope within circular economy principles: a critical review. Architect Eng Des Manag 2022;18:387–409.
[62] Sommese F, Badarnah L, Ausiello G. A critical review of biomimetic building envelopes: towards a bio-adaptive model from nature to architecture. Renew Sustain Energy Rev 2022;169:112850.
[63] Vanaga R, Blumberga A, Gusca J, Blumberga D. Choosing the best nature's strategy with the highest thermodynamic potential for application in building thermal envelope using MCA analysis. Energy Proc 2018;152:450–5.
[64] Gosztonyi S. The role of geometry for adaptability: comparison of shading systems and biological role models. J Facade Des Eng 2018;6:163–74.
[65] Al-Masrani SM, Al-Obaidi KM, Zalin NA, Isma MIA. Design optimisation of solar shading systems for tropical office buildings: challenges and future trends. Sol Energy 2018;170:849–72.
[66] Badarnah L. Form follows environment: biomimetic approaches to building envelope design for environmental adaptation. Buildings 2017;7:40.

[67] Fiorito F, Sauchelli M, Arroyo D, Pesenti M, Imperadori M, Masera G, et al. Shape morphing solar shadings: a review. Renew Sustain Energy Rev 2016;55:863–84.

[68] Sommese F, Hosseini SM, Badarnah L, Capozzi F, Giordano S, Ambrogi V, et al. Light-responsive kinetic façade system inspired by the Gazania flower: a biomimetic approach in parametric design for daylighting. Build Environ 2024;247:111052.

[69] Badarnah L, Knaack U. Shading/energy generating skin inspired from natural systems. Proceedings of the SB08: world sustainable building conference. 2008. p. 21–5. Melbourne, Australia.

[70] Chen D, Chen HW. Using the Köppen classification to quantify climate variation and change: an example for 1901–2010. Environ Dev 2013;6:69–79.

[71] Soliman ME, Bo S. An innovative multifunctional biomimetic adaptive building envelope based on a novel integrated methodology of merging biological mechanisms. J Build Eng 2023:106995.

[72] Charpentier L, Cruz E, Nenov T, Guidoux K, Ware S. Pho'liage: towards a kinetic biomimetic thermoregulating façade. Bionics Sustain Des n.d.:367.

[73] Chen E, Lu G, Barnik L, Correa D. Fast and reversible bistable hygroscopic actuators for architectural applications based on plant movement strategies. In: Proceedings of the International Conference on Education and Research in Computer Aided Architectural Design in Europe. 1; 2022. p. 261–70.

[74] Hosseini SM, Mohammadi M, Schröder T, Guerra-Santin O. Bio-inspired interactive kinetic façade: using dynamic transitory-sensitive area to improve multiple occupants' visual comfort. Front Architect Res 2021;10:821–37.

[75] Kuru A, Oldfield P, Bonser S, Fiorito F. Performance prediction of biomimetic adaptive building skins: integrating multifunctionality through a novel simulation framework. Sol Energy 2021;224:253–70.

[76] Sharp AB, Blay G, Kholodova J, Correa D. An autonomous bio-inspired shading façade system based on plant movement principles. Struct Optimiz MaterBased Des 2021.

[77] Hosseini SMM, Fadli F, Mohammadi M. Biomimetic kinetic shading facade inspired by tree morphology for improving occupant's daylight performance. J Daylight 2021;8:65–82.

[78] Fu SC, Zhong XL, Zhang Y, Lai TW, Chan KC, Lee KY, et al. Bio-inspired cooling technologies and the applications in buildings. Energy Build 2020;225:110313.

[79] Panya DS, Seo JH, Park HJ, Choo SY. A study of kinetic façade modelling performance using virtual reality. In: ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction. 36; 2019. p. 356–9. IAARC Publications.

[80] Khosromanesh R, Asefi M. Form-finding mechanism derived from plant movement in response to environmental conditions for building envelopes. Sustain Cities Soc 2019;51:101782.

[81] Sheikh WT, Asghar Q. Adaptive biomimetic facades: enhancing energy efficiency of highly glazed buildings. Front Architect Res 2019;8:319–31.

[82] Körner A, Born L, Mader A, Sachse R, Saffarian S, Westermeier AS, et al. Flectofold—a biomimetic compliant shading device for complex free form facades. Smart Mater Struct 2017;27:17001.

[83] Vanaga R, Purvins R, Blumberga A, Veidenbergs I, Blumberga D. Heat transfer analysis by use of lense integrated in building wall. Energy Proc 2017;128:453–60.

[84] Schleicher S, Lienhard J, Poppinga S, Speck T, Knippers J. A methodology for transferring principles of plant movements to elastic systems in architecture. Comput Aided Des 2015;60:105–17. https://doi.org/10.1016/j.cad.2014.01.005.

[85] Figliola A, Rossi M. Parametric design for technological and" smart" system. Adaptive and optimized skin. 30th international PLEA conference. 2014.

[86] Weston M, Greenberg D. Sweetgum Panels: a periodic compliant mechanism for solar shading. eCAADe 2013: Computation and performance–Proceedings of the 31st international conference on Education and research in computer aided architectural design in Europe. September 18-20, 2013. Delft, The Netherlands.

[87] Institute of Building Structures and Structural Design. FLECTOFOLD Demonstrator n.d. https://www.itke.uni-stuttgart.de/research/built-projects/flectofold-demonstrator/(accessed January 16, 2025).

[88] Taylor & Francis n.d. https://www.tandfonline.com/. [Accessed 16 January 2025].

[89] Van Eck NJ, Waltman L. VOSviewer manual. Leiden: Univeristeit; 2018. Leiden 2013.

[90] Jones HG, Rotenberg E. Energy, radiation and temperature regulation in plants. Encycloped Life Sci 2001:1–7.

[91] Imani N, Vale B. Developing a method to connect thermal physiology in animals and plants to the design of energy efficient buildings. Biomimetics 2022;7:67.

[92] Loonen RCGM, Trčka M, Cóstola D, Hensen JLM. Climate adaptive building shells: state-of-the-art and future challenges. Renew Sustain Energy Rev 2013;25:483–93.

[93] Atzeri A, Cappelletti F, Gasparella A. Internal versus external shading devices performance in office buildings. Energy Proc 2014;45:463–72.

[94] Nagy Z, Svetozarevic B, Jayathissa P, Begle M, Hofer J, Lydon G, et al. The adaptive solar facade: from concept to prototypes. Front Architect Res 2016;5:143–56. https://doi.org/10.1016/j.foar.2016.03.002.

[95] Jalali Sara, Nicoletti Eleonora, Badarnah Lidia. Potential applications of photovoltaic technologies for biomimetic adaptive solar building envelopes. Ipswich, UK: University of Suffolk; 2023.

[96] Knaack U, Klein T. The future envelope 1: a multidisciplinary approach, vol. 8. IOS Press; 2008.

[97] livMatS biomimetic shell [n.d].

[98] Zhan T, Li R, Liu Z, Peng H, Lyu J. From adaptive plant materials toward hygro-actuated wooden building systems: a review. Constr Build Mater 2023;369:130479. https://doi.org/10.1016/j.conbuildmat.2023.130479.

[99] Erb RM, Sander JS, Grisch R, Studart AR. Self-shaping composites with programmable bioinspired microstructures. Nat Commun 2013;4:1712.

[100] Kay R, Nitièma K, Correa D. The bio-inspired design of a self-propelling robot driven by changes in humidity. In: Proceedings of the 38th eCAADe Conference. 18; 2020. p. 233–42. Berlin Germany.