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Review

Biomimetic Climate-Adaptive Building Envelopes: Mapping Research Trends and Assessing Technology Readiness Towards Real-World Implementation

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Abstract

The building envelope is a key lever for reducing energy demand and carbon emissions in the built environment. However, conventional envelope systems remain largely static and are unable to respond effectively to changing climatic conditions. Biomimetics has emerged as a promising approach for the development of climate-adaptive envelope solutions. Nevertheless, research in this field remains fragmented across disciplines, and its evolution and technological maturity have not yet been systematically assessed. This study proposes an integrated analytical framework combining a bibliometric analysis of 2.007 Scopus-indexed documents, based on a VOSviewer keyword co-occurrence network, with a cluster-guided state of the art review, and a Technology Readiness Level (TRL) assessment of selected biomimetic envelope solutions. The TRL assessment is conducted using explicit operational criteria. The analysis identifies three main research clusters: (C1) environmental-performative, focusing on energy efficiency and envelope optimisation; (C2) material-experimental, addressing biomimetic composites and innovative materials; and (C3) technological fabrication, centred on digital fabrication, smart materials, and 4D printing. Temporal trends reveal a shift after 2018 from materials science-oriented studies towards computational design and adaptive manufacturing, providing quantitative evidence of a transition previously described mainly in qualitative terms. The review highlights a strong focus on solar-shading applications, while energy harvesting and passive thermoregulation remain comparatively underexplored. The TRL assessment shows that more than 80% of the analysed solutions are concentrated at TRL 3, indicating an early stage of technological development. The main barriers include limited material durability, non-standardised production costs, and regulatory constraints. The findings suggest that future progress will depend less on the identification of new biological inspirations and more on advancing the technological maturity and industrial scalability of existing concepts. This will require integrated developments in materials, parametric design, life-cycle assessment, and regulatory frameworks.

Keywords: biomimicry; responsive architecture; climate-responsive; kinetic façade; smart materials; additive manufacturing; 3D printing; 4D printing; architectural engineering

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1. Introduction

The building sector is globally responsible for approximately 36% of final energy consumption and around 37% of energy-related CO_2 emissions [1]. In this context, the building envelope, as the primary interface between indoor conditions and external climate [2,3], represents a key lever for reducing energy demand and enhancing environmental performance [4–6]. However, conventional envelope systems remain largely static, responding to climatic variability through fixed properties rather than adaptive behaviour [3,7]. The limitations of static envelopes are increasingly evident in the context of climate change: fixed thermal mass, non-responsive shading elements and passive glazing systems cannot adequately address the dynamic and site-specific nature of solar radiation, wind patterns and occupant behaviour. This has driven growing interest in climate-adaptive building envelopes, systems designed to modulate their optical, thermal and aerodynamic properties in response to changing environmental conditions, thereby optimising energy flows, reducing reliance on active HVAC systems, and enhancing indoor comfort [8–10]. Within this framework, nature offers an unparalleled repository of adaptive strategies refined over millions of years of evolutionary pressure [11]. Biological systems achieve high-performance environmental regulation through elegant, resource-efficient mechanisms that operate without external energy input: the hygroscopic bilayer structure of pine cones opens and closes in response to humidity; the thermoregulatory organisation of termite mounds maintains stable internal temperatures despite extreme external fluctuations; and the stomatal distribution of plant leaves modulates gas exchange and water loss in a decentralised, stimulus-responsive manner [12].

Biomimetics, defined as the study and translation of biological principles, structures and processes into technical applications, provides a methodological framework for transferring such strategies to architectural engineering, particularly in the design of climate-adaptive building envelopes [13,14]. Since the pioneering work of Benyus [15], the field has undergone substantial expansion, progressively incorporating computational design, advanced manufacturing and material science into its operative toolkit. A fundamental evolution has characterised the field over the past two decades: from morphological–structural emulation, in which biological forms are replicated primarily for aesthetic or structural purposes, toward dynamic-functional emulation, in which the adaptive behaviours and stimulus-response mechanisms of living organisms are translated into building systems capable of autonomous environmental regulation [16,17]. In this transition, plants have emerged as the predominant source of biological inspiration, owing to their capacity to adapt to environmental stimuli while remaining in a fixed position, a condition directly analogous to that of building envelopes [2,12]. Concurrently, the integration of smart materials, including shape memory alloys (SMAs), shape memory polymers (SMPs), thermobimetals and hygroscopic composites, has been identified as a key enabling factor, allowing the replacement of energy-intensive mechanical actuation systems with passive or semi-passive material responses [18].

The transfer from biology to building envelopes is also epistemologically non-trivial, particularly because the field is characterised by a heterogeneous and only partially standardised terminology. Bionics, coined in 1960, denotes the adaptation of biological system properties to technological processes without a specified scope or methodology, and it has progressively narrowed toward robotics and medical applications [19]. Biomimetics and biomimicry, by contrast, are more consistently defined around the functional bases of biological forms, processes and systems - namely, the deliberate emulation of a biological mechanism to solve a design problem, while bio-inspired and nature-inspired are used more loosely across the literature to describe design approaches that draw on biological references at large, without necessarily requiring functional equivalence [2,20]. In this study, these terms are treated as related but non-interchangeable, and the analysis is restricted to functional emulation: the reproduction of a biological mechanism's behaviour (a stimulus-response principle, an actuation logic, or a regulatory strategy) rather than of its outward form. This restriction follows directly from the object of study: climate-adaptive building envelopes must reproduce a dynamic behaviour, not an appearance, and morphological resemblance to a biological model, in the absence of functional transfer, does not constitute climate-adaptive capacity.

A further boundary concerns the object of emulation itself. This study is concerned with biomimetics as the abstraction of a biological principle into a synthetic, non-living technical solution, as opposed to bio-utilisation, in which living organisms or ecosystems are directly incorporated into a building or its surroundings, as in nature-based solutions, green façades or biophilic design [21–23]. While these approaches share a common reference to biological systems and can pursue overlapping climate-adaptive goals, they operate through fundamentally different mechanisms of integration, and the latter falls outside the scope of the present review.

Biological mechanisms operate at scales, material compositions, energy regimes and evolutionary timeframes that differ radically from architectural systems. Therefore, this study does not assume direct translatability. Instead, biological references are interpreted as abstractions that require engineering translation through material substitution, performance modelling, manufacturability constraints, durability testing and building-code compatibility.

Despite significant advances, research on biomimetic climate-adaptive building envelopes remains fragmented across disciplinary domains, and a comprehensive understanding of its thematic structure, temporal evolution, and technological maturity is still lacking. To address this gap, this study combines bibliometric mapping, a cluster-guided literature review, and Technology Readiness Level (TRL) assessment to provide a systematic overview of the field and its development trajectory.

Research Gap and Study Contributions

Despite the growing body of research on biomimetic design and adaptive building envelopes, the field remains fragmented across multiple disciplinary domains, including environmental performance, material innovation, computational design, and fabrication technologies. Existing reviews have primarily focused on specific biomimetic strategies, material systems, or performance-oriented applications [3,24–26]. However, three interrelated limitations persist in the current literature.

First, existing reviews identify recurrent findings, including the low technological maturity of most solutions, the functional bias toward solar shading over energy harvesting and thermoregulation, and the transition from morphological to dynamic-functional biomimicry, primarily through qualitative case selection rather than a quantitative or bibliometrically structured basis. This limits the replicability and comparability of their conclusions across studies.

Second, while the fragmentation of the field across environmental performance, material science, and fabrication technologies has been repeatedly noted, how these domains are interconnected, how they have evolved over time, and which are currently driving the research frontier have not been systematically mapped. As a result, it remains unclear which thematic domains are leading current development and to what extent they are converging toward deployable solutions.

Third, assessments of technological maturity in the existing literature are largely informal, based on implicit judgements rather than explicit and uniform criteria. No previous review has applied a structured TRL framework with operationally defined correspondence criteria across a systematically selected corpus of biomimetic envelope solutions, preventing meaningful cross-study comparison of implementation readiness.

To address these gaps, this study combines bibliometric mapping, a cluster-guided literature review, and TRL assessment to investigate the current state and development trajectory of biomimetic climate-adaptive building envelopes. Through the integration of quantitative and qualitative analyses, the research aims to provide a structured understanding of the field while identifying the main barriers and opportunities for future technological transfer.

The main contributions of this study are threefold: (i) to provide the first bibliometrically grounded mapping of research on biomimetic climate-adaptive building envelopes, identifying the principal thematic domains, their structural interrelations, and their temporal evolution—thereby dating and spatialising disciplinary transitions that existing reviews have described only narratively; (ii) to develop a cluster-guided state of the art review that quantifies functional and material biases across the field, including the underrepresentation of energy harvesting and thermoregulation strategies relative to solar shading; and (iii) to assess the technological maturity of representative biomimetic envelope systems through a structured TRL framework with explicit operational criteria, enabling, for the first time, a systematic and comparable evaluation of implementation readiness across solution typologies.

2. Methodology

2.1. Bibliometric Analysis and VOSviewer Mapping

A bibliometric analysis was conducted to investigate the conceptual structure and thematic evolution of research at the intersection of biomimetics and adaptive building envelope technologies. The dataset was retrieved from the Scopus database in April 2026. The search strategy was applied to the TITLE, ABSTRACT, and KEYWORD fields using the following query: *(((“biomimicry” OR “biomimetics” OR “biomimetic” OR “bioinspired” OR “bio-inspired” OR “nature-inspired” OR “bionics”) AND (“architecture” OR “built environment” OR “building” OR “facade” OR “building envelope” OR “adaptive building” OR “building skin” OR “urban environment” OR “construction material”) AND (“thermal performance” OR “thermal regulation” OR “passive cooling” OR “passive ventilation” OR “daylighting” OR “energy efficiency” OR “structural optimization” OR “shell structure” OR “adaptive facade” OR “smart material” OR “parametric design” OR “generative design” OR “computational design” OR “digital fabrication” OR “biomimetic material” OR “bio-based” OR “living material”))).*

The query is structured in three mandatory AND blocks: the first captures the principal terminological variants of biomimetic and bio-inspired design; the second restricts results to the architectural and built environment domain; the third filters for performance-oriented, material, or fabrication-related applications, ensuring thematic relevance to climate-adaptive envelope systems. No temporal restrictions were applied.

The broad terminological block was intentionally adopted as a recall-oriented strategy because authors in architecture, materials science and engineering frequently use biomimicry, biomimetics, bio-inspired, nature-inspired and bionics with overlapping but non-identical meanings. The breadth of the first block was counterbalanced by the architectural and performance/material/fabrication blocks and by the subsequent two-stage screening. This choice increased initial noise, including biomedical, neuromorphic-computing and robotics records, but reduced the risk of excluding relevant architectural studies solely because they adopted a different disciplinary vocabulary.

At the same time, the three-block AND structure is a conservative search logic and may generate false negatives. Papers that address a biomimetic envelope solution but omit one of the three keyword categories in the title, abstract or author keywords can be missed. For this reason, the bibliometric dataset should be interpreted as a reproducible corpus rather than as an exhaustive census of all relevant work. The cluster analysis therefore maps the most visible and consistently indexed portion of the field, while the qualitative review complements it through relevance-based screening of envelope-oriented contributions.

Scopus was selected as the sole database because of its broad coverage of engineering, architectural technology, materials science and conference-indexed literature, as well as the consistency of its exportable author-keyword metadata required for VOSviewer analysis.

The search yielded a total of 2007 documents, which were included in the bibliometric analysis (subsequent database updates may produce marginally different results).

Keyword co-occurrence analysis was employed to identify the main research themes and their interrelationships within the scientific literature. The analysis was performed using VOSviewer (version 1.6.18) [27], based exclusively on author keywords. A full counting method was applied to construct the bibliometric network. The analysis focused on identifying the frequency with which keywords co-occurred within the same publications, thereby capturing conceptual associations and thematic linkages across the field. To ensure interpretability of the network, a minimum occurrence threshold of eight was applied, in order to balance network readability with sufficient thematic coverage. Only keywords meeting this threshold were included in the final visualisation, allowing the identification of the most representative and consolidated research themes while reducing noise from infrequently used terms.

Prior to network construction, the keyword list was manually cleaned to reduce artificial fragmentation. Singular/plural variants, hyphenation variants and spelling variants were merged where they clearly referred to the same concept (e.g., bioinspired/bio-inspired, facade/façade, additive manufacturing/3D printing, where appropriate, only when used synonymously in the record context). Generic or off-scope high-frequency terms emerging from excluded domains were removed after screening when they did not contribute to architectural interpretation. Duplicate records generated by database export were checked before VOSviewer import. These cleaning decisions were applied conservatively so that emerging but meaningful terms were not automatically suppressed.

In the resulting network maps, each node represents a keyword, while links between nodes indicate co-occurrence relationships. Node size reflects keyword frequency, whereas link strength represents the intensity of co-occurrence [23,28,29]. The spatial proximity between nodes indicates the strength of their conceptual relatedness, with closely positioned nodes representing stronger thematic associations. Keywords with similar co-occurrence patterns are grouped into clusters representing major research themes within the field.

Two complementary visualisation modes were employed. First, a network visualisation was used to examine the structural organisation of the research landscape, highlighting thematic clusters and their interconnections. Second, an overlay visualisation was generated to explore temporal trends within the literature. In this representation, node colours correspond to the average publication year of the documents associated with each keyword, enabling the identification of emerging topics and more established research topics.

The combined use of network and overlay visualisations provides both a static representation of the field's conceptual architecture and a temporal perspective on its development. It should be noted that keyword co-occurrence networks do not measure scientific impact or citation performance; rather, they reveal patterns of thematic proximity and knowledge organisation within the scientific literature.

Notably, the VOSviewer analysis was used as an exploratory mapping tool rather than as a definitive classification of the field; its methodological limitations are discussed in Section 5.3.

2.2. State of the Art Review

Complementing the bibliometric mapping, a structured and analytically guided review of biomimetic solutions for climate-adaptive building envelopes was conducted. Rather than being conceived as a narrative synthesis, the review was systematically organised based on the three thematic clusters identified through the co-occurrence analysis (environmental-performative, material-experimental, and technological fabrication), which provided the conceptual framework for the literature classification and interpretation.

Prior to the qualitative synthesis, the retrieved dataset of 2.007 documents underwent a two-stage screening process (Figure 1). In the first stage, documents were excluded when their primary focus fell outside the scope of the present research: papers addressing biomedical applications of biomimetic principles, including tissue engineering, bone regeneration, scaffold design for clinical implantology, and wound healing, were removed, as they share terminological overlap with the search strategy but bear no relevance to architectural or envelope systems. Similarly, papers focused on neuromorphic computing, including spiking neural networks, memristor-based devices, and brain-inspired electronic architectures and on bio-inspired robotics, including soft robots, locomotion systems, and autonomous underwater vehicles, were excluded. The remaining 1664 documents were retained for stage 2 relevance screening.

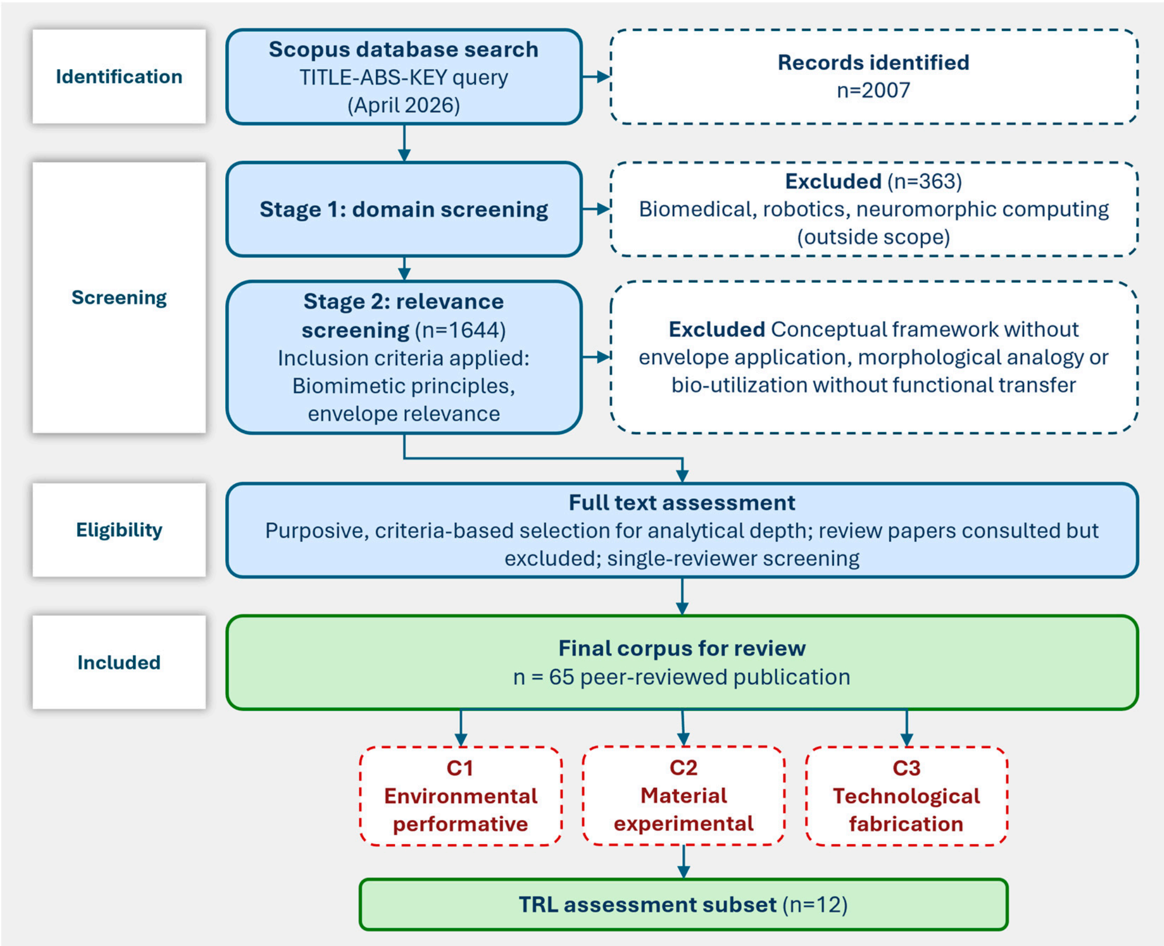

Figure 1. Flow diagram of the literature screening and selection process.

Publications were selected according to predefined inclusion criteria, requiring (i) an explicit application of biomimetic or bio-inspired principles; (ii) a direct relevance to building envelope systems, including façades, building skins, cladding systems, or roof components; and (iii) a functional biological reference, that is, the transfer of a biological mechanism, stimulus-response principle or regulatory behaviour into the envelope system, rather than a purely formal or morphological analogy, or the direct incorporation of living organisms into the envelope (bio-utilisation). Studies limited to formal/morphological resemblance or to bio-utilisation were therefore excluded, even where self-labelled as biomimetic (e.g., green façade and living-wall systems incorporating live vegetation or microorganisms [30,31]). Studies focusing exclusively on conceptual frameworks without application-oriented relevance to envelope performance were excluded. Review papers were consulted for contextual understanding but were not included among the analysed case studies. Both experimental and simulation-based studies were considered, provided that they reported measurable or modelled performance outcomes. No temporal restriction was applied to the retrieval; the reviewed corpus reflects a literature base dominated by publications from 2022 onwards, consistent with the accelerating growth of the field observed in the bibliometric analysis. In the second stage, a relevance-based selection was applied to the domain-screened corpus to identify the most significant contributions for qualitative synthesis. Given the breadth and heterogeneity of the retrieved literature, a purposive selection strategy was adopted to ensure analytical depth while maintaining representation of the principal thematic domains identified through the bibliometric analysis. Selection prioritised studies presenting the strongest and most explicit thematic alignment with the three identified clusters, operationally defined as full satisfaction of criteria (i)–(iii) above, rather than an independent subjective judgement. Studies in which biomimetic terminology appeared marginally or in generic terms, without a specific application to envelope systems, were excluded at this stage. The screening process yielded a final corpus of 65 peer-reviewed publications, organised according to the three thematic clusters identified through the bibliometric analysis, comprising environmental-performative studies, material-experimental studies, and technological fabrication studies. Screening and selection at both stages were conducted by the sole author of this study; independent dual screening and inter-reviewer agreement metrics were therefore not applicable.

From this corpus, a subset of several representative biomimetic envelope solutions was selected for comparative TRL assessment. Selection was based on the direct application of biomimetic principles to climate-adaptive building envelope systems, the availability of sufficient technical and performance information, and the representativeness of different biological models, adaptive strategies, and material-technological approaches identified across the reviewed literature. The resulting sample formed the basis for the comparative TRL assessment presented in Section 2.3, aimed at evaluating the maturity and implementation readiness of current biomimetic envelope solutions.

2.3. Technology Readiness Level Assessment

To enable a standardised and comparative evaluation of technological maturity across representative biomimetic envelope solutions, a TRL assessment was conducted for the twelve case studies selected from the reviewed literature. The assessment followed the framework established by the European Commission [32,33].

The TRL classification was based on the level of validation reported in each study, including numerical simulation, laboratory-scale prototyping, and full-scale demonstration under controlled or real environmental conditions. When TRL levels were not explicitly reported, they were consistently inferred from the description of the development stage and validation procedures, using a uniform decision rule applied across all cases to minimise subjectivity and ensure comparability. To support the transparency and replicability of TRL attributions, a structured correspondence table was adopted, mapping each TRL level to explicit operational criteria: TRL 1–2 was assigned to studies identifying a biological principle without quantitative modelling, TRL 3–4 to studies reporting numerical simulation or reduced-scale proof of concept, TRL 5–6 to laboratory-validated prototypes tested under controlled conditions, TRL 7–8 to full-scale demonstrations or real-environment pilot installations, and TRL 9 to systems documented as operational within actual building contexts. This approach enabled a coherent comparative assessment of biomimetic envelope solutions in terms of technological maturity and implementation readiness.

The TRL values reported in Section 4.5 refer to the maturity of the biomimetic envelope solution as documented in the analysed publication, not to the market maturity of every component technology in isolation. For example, electrochromic glass is commercially available and has been installed in real buildings; nevertheless, when a cited study evaluates a bio-inspired façade configuration mainly through simulation or early-stage design integration, the solution is classified at the corresponding article-specific TRL. The assessment therefore avoids equating the commercial availability of a material with the validated readiness of a complete biomimetic adaptive-envelope system.

3. Bibliometric Results

3.1. Network Structure and Cluster Identification

The VOSviewer co-occurrence analysis (Figure 2) identifies three principal semantic clusters (C1–C3) that structure the intersection of biomimetics and architectural engineering. These clusters are not isolated domains but mutually connected sub-networks, reflecting the inherently interdisciplinary character of the field. Table 1 summarises their composition and key characteristics.

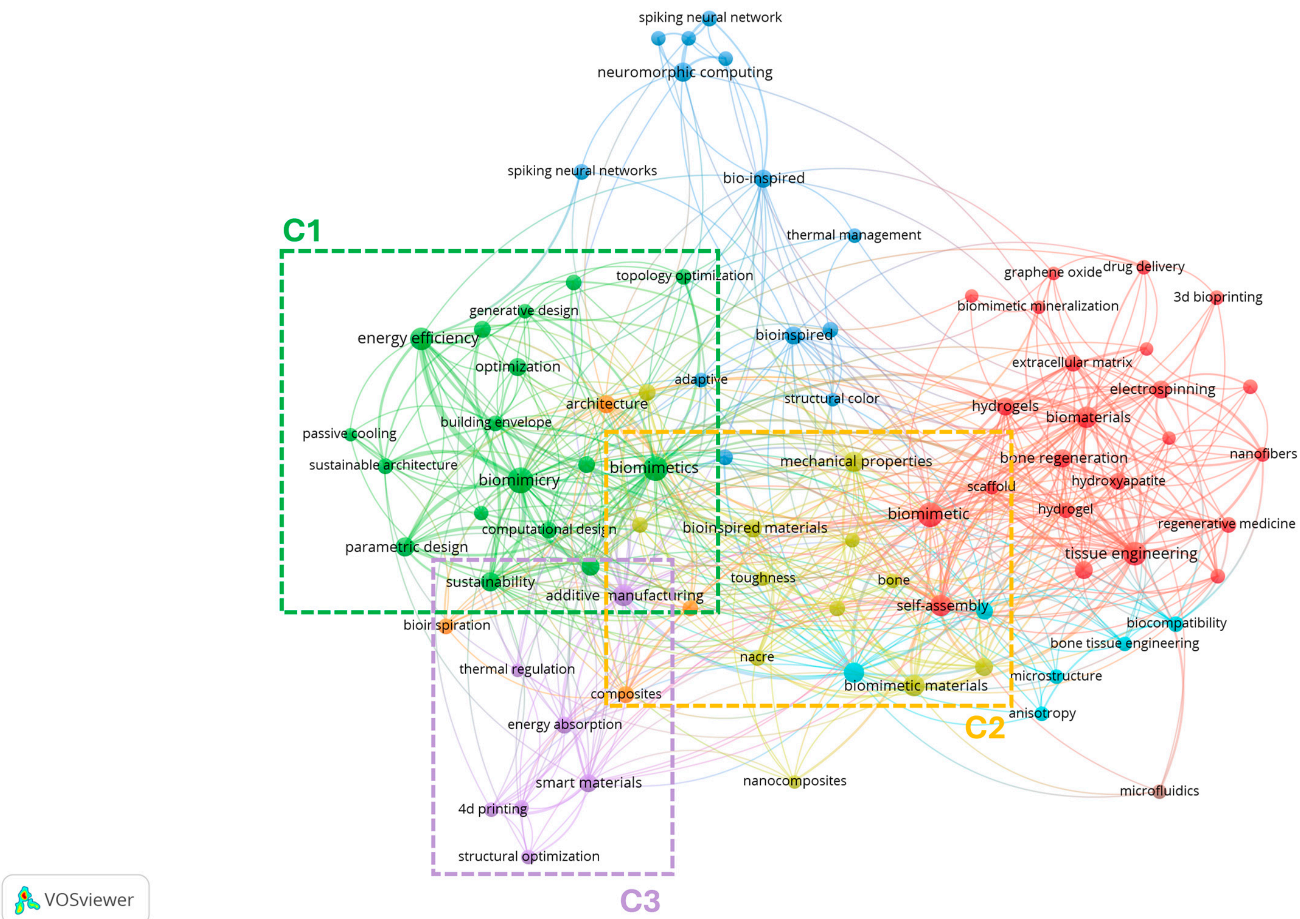

Figure 2. Network visualisation of keyword co-occurrences in the analysed dataset. Identification of three main clusters: cluster 1 (green)—17 items related to environmental-performative; cluster 2 (yellow)—12 items related to material-experimental; cluster 3 (purple)– 7 items related to technological fabrication. Created by VOSviewer software.

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Table 1. Main three clusters identified: keywords, focus, and temporal phase.

Cluster	Keywords	Focus	Temporal Phase	Items
C1 Environmental-Performative	Biomimicry, architecture, energy efficiency, passive cooling, building envelope, parametric design, sustainable architecture, optimisation	Climate-adaptive design, passive control, envelope performance	Intermediate (2010–2018)	17
C2 Material-Experimental	Biomimetic materials, bio-inspired materials, mechanical properties, composites, nanocomposites, self-assembly	Material science, structural biomimetics, experimental substrates	Early/Foundational (pre-2010)	12
C3 Technological Fabrication	Digital fabrication, additive manufacturing, smart materials, 4D printing, thermal regulation, structural optimisation, topology optimisation	Manufacturing processes, adaptive systems, responsive architecture	Recent (2018–present)	7

3.1.1. Cluster C1: Environmental-Performative

The first and most directly architecture-specific cluster organises around terms such as biomimicry, architecture, energy efficiency, passive cooling, building envelope, optimisation, parametric design and sustainable architecture. This cluster delineates an area in which biomimetics functions as a matrix of environmental and performative strategies aimed at improving the energetic and climatic behaviour of the building organism. The biological reference is no longer interpreted in purely analogical or morphological terms, but as a repertoire of operational principles transferable to technical design, particularly in relation to climate adaptation, passive control, energy efficiency and envelope performance optimisation. The presence of "parametric design" within this cluster signals the progressive integration of computational tools as mediators between biological inspiration and architectural application.

3.1.2. Cluster C2: Material-Experimental

The second cluster, positioned as a hinge with the more consolidated domains of biomimetic science, gathers terms including biomimetic materials, bio-inspired materials, mechanical properties, composites and nanocomposites. Although less directly architectural, this cluster is essential for clarifying the genealogy of the sub-field, as it represents the material and technological background from which technical architecture derives a significant part of its conceptual and applicative tools. The structure of the field, as it emerges from Figure 2, does not describe a linear transfer of biomimetics toward architecture, but rather the progressive convergence of three lines of development: environmental-performative, technological-productive and material-experimental, which find in architectural engineering a domain of synthesis and application.

3.1.3. Cluster C3: Technological Fabrication

The third cluster is more explicitly technological and procedural in character, organised around keywords including digital fabrication, additive manufacturing, smart materials, 4D printing, thermal regulation and structural optimisation. This cluster is particularly significant because it signals a phase of disciplinary advancement in which biomimetics no longer operates solely as a theoretical reference or design inspiration methodology but tends to be incorporated into production processes, constructive devices and the materialisation logics of architecture. The convergence between bio-inspiration, structural optimisation, smart materials and digital fabrication suggests the consolidation of a distinctly technical–

architectural orientation, in which the building is conceived as a dynamic, adaptive and performative system.

3.2. Temporal Dynamics and Disciplinary Trajectory

The temporal overlay visualisation (Figure 3) introduces the time variable and enables a reading of the field's transformation in evolutionary terms. The overlay shows that terms belonging to the domain of biomaterials, tissue engineering and self-assembly processes tend to occupy the relatively older portions of the network, indicating that biomimetics, in its initial phase, developed predominantly within a scientific–material horizon external to architectural design.

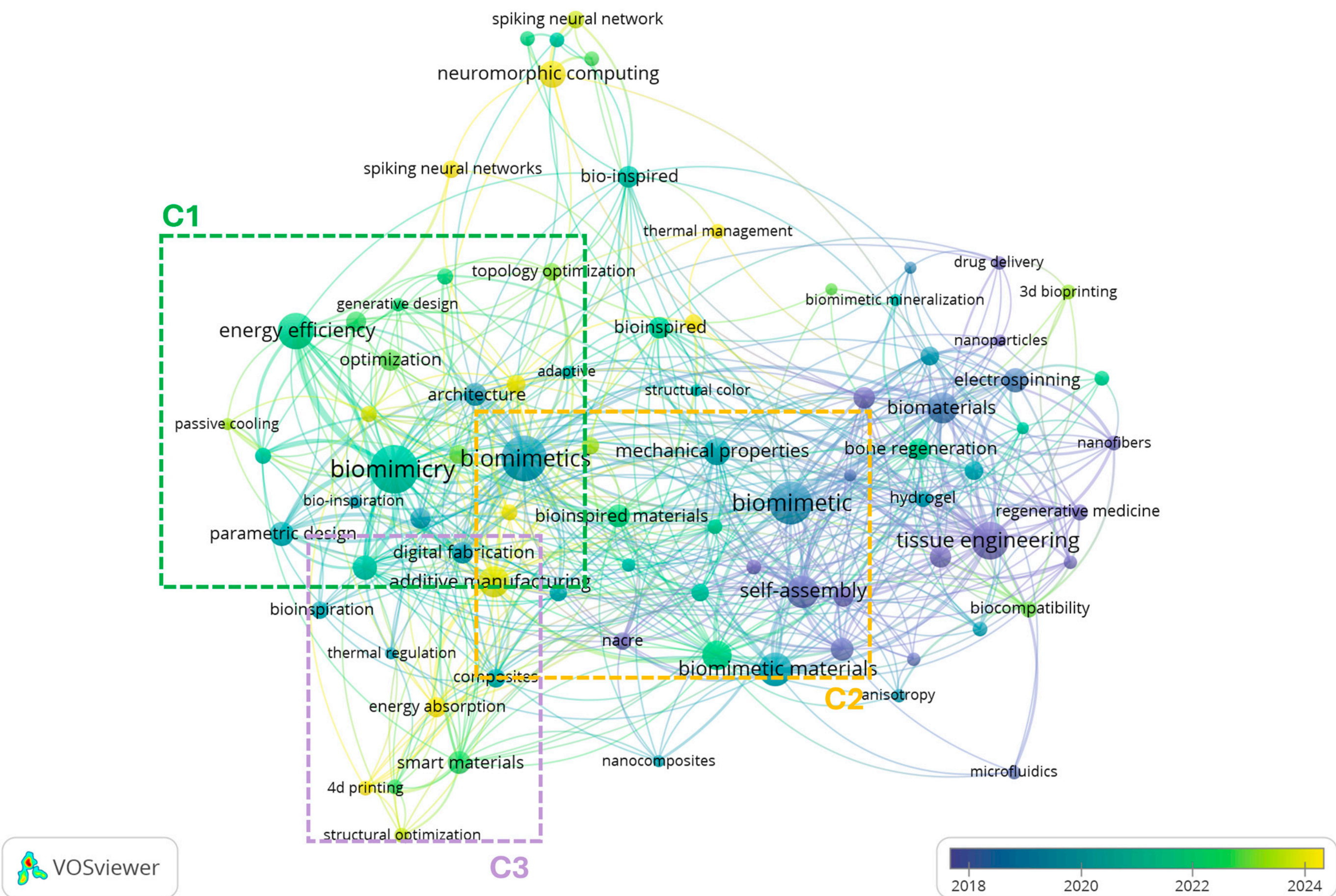

Figure 3. Overlay visualisation of keywords co-occurrences in the analysed dataset. Identification of three main clusters: cluster 1 (green); cluster 2 (yellow); cluster 3 (purple). Created by VOSviewer software.

More recent nodes cluster around the C1 terms (biomimicry, biomimetics, architecture, energy efficiency, parametric design and bio-inspiration), testifying to the progressive reworking of biomimetics as an operative tool for addressing central questions of contemporary technical architecture: energy reduction, environmental comfort, envelope optimisation, and the integration of form, structure and performative behaviour.

The most significant evolutionary signal, however, is the emergence of Cluster C3 terms (digital fabrication, additive manufacturing, smart materials, 4D printing, topology and structural optimisation) in the most recent portions of the network. Their position demonstrates that the most advanced developments of biomimetics in architectural engineering currently concentrate on the translation of bio-inspired principles into generative, simulation and construction procedures. Biomimetics is thus configuring itself not merely as an inspirational paradigm or conceptual repertoire, but as a techno-operative platform capable of informing simultaneously the ideative, computational and productive levels of design.

This bibliometric evidence confirms that the sub-field has reached a sufficient level of disciplinary maturity to be studied systematically and that its most pressing research frontier lies at the intersection of adaptive materials, computational design and digital fabrication.

3.3. Post-2018 Acceleration and Emerging Research Frontier

The post-2018 period is characterised by a clearer convergence between computational design, programmable materials and digitally fabricated adaptive components. In the overlay map, the most recent terms concentrate around digital fabrication, additive manufacturing, 4D printing, smart materials, topology optimisation and structural optimisation. This indicates that the frontier has shifted from identifying biological analogies toward embedding stimulus-response behaviour into materials and manufacturing workflows. Three developments are particularly important. First, 4D printing enables hygromorphic or thermoresponsive components in which movement is programmed through anisotropic material organisation rather than through motors. Second, AI-assisted and generative design workflows increasingly support the exploration of large biomimetic design spaces, although their presence remains weak in the keyword network because terminology is fragmented. Third, smart materials such as SMPs, SMAs, thermobimetals, electrochromic systems and hygroscopic composites create a bridge between biological principles and constructible façade elements. The main challenge after 2018 is therefore not only conceptual invention but validation: long-term cyclic durability, controllability, fire and safety compliance, maintainability and cost-effective fabrication remain insufficiently demonstrated.

4. State of the Art: Biomimetic Solutions for Climate-Adaptive Building Envelopes

The application of biomimetic principles to building façades represents one of the most dynamic and promising research threads in contemporary technical architecture [34]. In this context, the building envelope is progressively reinterpreted not as a static separation element between interior and exterior, but as a dynamic, adaptive and performative system capable of actively and passively regulating energy, light and thermohydric flows [35]. The climate-adaptive building envelope represents a technological solution designed to respond to environmental variations, thereby optimising energy flows, reducing power consumption for lighting and HVAC systems, and enhancing indoor comfort [8–10]. The state of the art reveals a growing integration among bio-inspired design approaches, material innovation, advanced simulation tools and digital fabrication techniques [36,37].

4.1. Biological Models and Design Analogies

Biomimetic research applied to building façades develops primarily according to a top-down (problem-driven) approach, in which specific design challenges, such as solar radiation control, thermal flux regulation and daylight management, are addressed through the identification of functional analogies in the natural world [13,38,39]. Sources of biological inspiration are heterogeneous, spanning plant systems, animal structures and cellular models [40].

In the plant domain, nastic movements, such as the opening and closing of petals in Gazania species [41] or the leaf-rolling mechanisms of Ammophila arenaria [42], have inspired solar shading systems capable of modifying their configuration in response to environmental stimuli without mechanical actuation energy. Cellular systems, particularly the distribution and functioning of stomata, have been adopted as models for developing façades with Transient Sensitive Areas (TSAs), capable of responding in a decentralised manner to microclimatic conditions or occupant presence [43]. In the animal domain, structures such as the wings of the Morpho butterfly offer examples of optical optimisation for light reflection and diffusion, while historical devices such as Persian Orosi windows represent an intriguing convergence between bio-inspired principles and traditional constructive techniques [44].

A representative example is the Gazania-inspired light-responsive kinetic façade [41]. The concept abstracts the flower opening mechanism into a shading element whose expansion and contraction respond to light exposure through a programmable polymeric behaviour. Its expected benefit is the reduction of glare and excessive solar gain without relying on conventional motorised louvres. The main barrier is that performance has so far been evaluated primarily through daylight simulation and controlled material response rather than through long-term façade operation, leaving durability, repeatability and maintenance unresolved.

4.2. Smart Materials and Adaptive Systems

A central element in the development of biomimetic façades is material innovation, which enables the replacement of complex and energy-intensive mechanical systems with passive or semi-passive solutions [45]. Smart materials play a determining role, allowing the realisation of components capable of autonomously responding to environmental stimuli [18,24,46].

Among the most widely studied solutions are bimetallic strips, composed of layers with different thermal expansion coefficients, which generate bending movements in response to temperature variations [42,47]. Shape memory alloys (SMAs) are employed as passive actuators capable of modifying their configuration under solar heat, activating ventilation or shading systems [48]. Shape memory polymers (SMPs), both thermosensitive and photosensitive (e.g., azobenzene-based), extend applicative possibilities, allowing finer programming of material responses [41]. The integration of smart glazing systems, electrochromic or photochromic, enables dynamic modulation of transparency and solar gain, often in combination with kinetic systems [49]. An emerging thread is represented by bio-based hygroscopic materials, particularly cellulose-based composites, used to develop actuators that respond to variations in relative humidity without external energy input [50,51].

The bio-inspired adaptive system based on iris-like motion and electrochromic glass [49] illustrates the hybridisation of bio-inspired design principles with an already industrialised smart material. Rather than relying on a single adaptive mechanism, the study integrates two biological references—stomata's patchy pattern and the morphology of the Iris flower—to inform a dynamic shading system, while the electrochromic glazing acts as a responsive optical layer. The benefit lies in the potential combination of geometric adaptation through kinetic shading and optical adaptation through smart glazing, improving daylight performance and glare control. The barrier is not the commercial availability of electrochromic glass itself, but the need to further validate the integrated biomimetic strategy, control logic, visual comfort outcomes and façade-level reliability under real-building conditions.

4.3. Simulation Methodologies and Physical Prototypes

Performance evaluation of biomimetic façades relies on an integrated approach combining parametric modelling, environmental simulation and physical experimentation [52]. Digital modelling tools, primarily Rhinoceros and Grasshopper, constitute the geometric and morphological definition basis, while specific plugins such as Ladybug and Honeybee enable climatic and daylighting analyses [53,54]. Thermal simulations are generally conducted through EnergyPlus and DesignBuilder, while tools such as DIVA permit the evaluation of advanced parameters, including spatial Daylight Autonomy (sDA) and Daylight Glare Probability (DGP). Structural and material behaviour is assessed through Finite Element Analysis (FEA) platforms such as ABAQUS, frequently coupled with parametric optimisation routines.

Despite the centrality of simulation, a significant portion of the research is oriented toward experimental validation through physical prototypes. Both 1:1 scale models, developed to test the kinetic behaviour of materials such as bimetallic or hygroscopic systems, and full-scale demonstrators have been produced. A representative lineage of this research is found in the work of the University of Stuttgart (ICD/ITKE), where several bio-inspired prototypes have progressively explored material-driven actuation and environmental responsiveness.

Among these, HygroSkin, Meteorosensitive Pavilion demonstrates the use of hygroscopic wood bilayers to achieve passive, humidity-driven actuation without mechanical or electrical input, enabling adaptive porosity modulation in response to atmospheric conditions [55]. Similarly, FlectoLine investigates fluid-driven structural deformation inspired by aquatic plant mechanics, integrating flexible composite elements to achieve controlled, reversible shape change under environmental loading [51]. These prototypes illustrate a transition from purely computational biomimetic design toward materially embedded computation, where environmental responsiveness is directly encoded into the physical properties of the envelope system.

A notable example is the livMatS Biomimetic Shell developed at the University of Stuttgart (ICD/ITKE), which employs hygroscopic bilayer wood composites to generate autonomous actuation in response to atmospheric humidity; its performance has been monitored over extended periods to assess weather robustness and reliability [56]. This case represents the current highest TRL (6) in bio-inspired adaptive envelope research.

4.4. Advanced Digital Fabrication: 3D and 4D Printing

The geometric and functional complexity of biomimetic façades requires recourse to advanced digital fabrication techniques. 3D printing is now a consolidated tool, employed both for the direct production of components and for the fabrication of moulds and matrices capable of imparting specific curvatures and properties to materials such as bimetallics [57,58].

3D printing has evolved into 4D printing through the integration of time as a fourth dimension, enabling objects to change their shape, properties, or functionality in response to external stimuli such as heat, light, or humidity [59–61]. Key advances include the use of smart materials, such as shape memory polymers, hydrogels, and metallic alloys, with applications ranging from self-expanding medical stents to deformable aerospace structures [59]. This technology enables the realisation of self-adaptive systems without mechanical moving parts, with potential advantages in terms of reduced maintenance, energy efficiency and production scalability. The alignment between 4D printing and biomimetic design principles is particularly significant: both share the logic of embedding function in material structure rather than in external mechanical control systems [62,63].

The 2025 weather-responsive adaptive shading system [64] exemplifies this trajectory. It uses bio-based hygromorphic 4D-printed filaments inspired by pine-cone actuation to generate curling movements under humidity variation. The concept embeds responsiveness in the printed material itself, offering the benefit of passive actuation and reduced operational energy. The main implementation barriers are reproducibility of printed anisotropy, long-term weathering, dimensional stability and translation from demonstrator geometry to code-compliant façade assemblies.

4.5. Systematic Overview of Biomimetic Envelope Solutions

Table 2 systematises twelve representative biomimetic envelope solutions selected from the reviewed literature and classified according to biological model, adopted strategy, application scale, smart material or technology employed, simulation methodology, TRL, and key limitations. Although not intended as a statistical representation of the entire field, the comparative assessment provides useful insights into the current state of technological development of biomimetic envelope systems. The analysed cases reveal a marked concentration at low Technology Readiness Levels, predominantly around TRL 3, with only a limited number of solutions reaching TRL 6. This pattern suggests that, despite the growing scientific interest in biomimetic adaptive envelopes, the transition from experimental research to real-world implementation remains limited.

From a functional perspective, the analysed cases show a strong convergence toward solar-responsive strategies, with solar radiation and light emerging as the dominant environmental triggers. Correspondingly, shading and regulation functions are consistently the most recurrent, confirming that current biomimetic research in façade systems is primarily oriented toward daylight modulation and thermal control rather than broader environmental or multi-functional performance.

At the material and technological level, a pattern of convergence can be observed around a limited set of enabling systems, including shape memory materials, hygroscopic composites and bimetallic elements, often coupled with parametric modelling environments such as Rhinoceros/Grasshopper and environmental simulation tools (e.g., Ladybug, Honeybee, and EnergyPlus). This suggests a partial consolidation of the technological toolkit, despite the experimental nature of most applications.

The predominance of low-TRL solutions highlights a structural gap between experimental research and real-world implementation, which directly informs the research agenda outlined in this study, prioritising the transition from prototype-based exploration to scalable, validated and deployable envelope systems. HygroSkin, FlectoLine and the livMatS Shell [56,64,65] represent notable exceptions, having reached TRL 6 through sustained physical testing. The primary bottlenecks—durability, fabrication cost, scalability and control integration—are consistent across solution typologies, suggesting that overcoming them requires systemic rather than incremental interventions.

These patterns show a clear correspondence with the three clusters identified in the bibliometric analysis. The predominance of shading and environmental regulation strategies reflects the environmental-performative cluster (C1), while the recurrent use of parametric modelling, simulation tools and adaptive systems aligns with the technological fabrication cluster (C3). At the same time, the central role of smart materials—including hygroscopic composites, shape memory materials and bio-inspired substrates—confirms the foundational contribution of the material-experimental cluster (C2). This alignment reinforces the interpretation of biomimetic envelope research as a field structured by the convergence of environmental performance, technological processes and material innovation.

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Table 2. Analysis of biomimetic adaptive façades. Climate [66]: BWh: hot desert; BSh/BSk: hot semi-arid steppe; Cfb: oceanic/subtropical highland; Csa: hot-summer Mediterranean; Dfb: humid continental. **Responsive function** [3]: Regulate (Reg), Shield (Sh). **Environmental trigger**: Sun (S), Light (L), Temperature (T), Humidity (H). **Analysis**: thermal comfort (T), daylight quality (DL). **Building use**: Educational (E), Office (O), Expositive (Ex). **Technological Readiness Levels** (TRL): 3 (simulation), 4–5 (prototype), 6 (real demonstration).

Object	Year	Building Use	Country	Climate	Responsive Function	Environmental Trigger	Movement	Material	Analysis	Tools/Software	Surface	Organism of Inspiration	TRL
Weather-responsive adaptive shading [64]	2025	Ex	Freiburg Germany	Dfb	Sh	H	Curling	Biological hygromorphic filament	T, DL	Real prototype	4D	Pine Cone	6
Biomimetic Kinetic Façade [53]	2025	O	Iran Yazd	BWh	Reg Sh	L	Open–closed	n/a	DL	Rhinoceros Grasshopper Climate Studio Design Explorer	3D	Venus Flytrap	3
Bio-inspired adaptive system [49]	2025	O	Iran Esfahan	BSk	Reg Sh	L	Folding	Electrochromic glass	DL	Rhinoceros Grasshopper Honeybee Ladybug Colibri	3D	Iris	3
FlectoLine façade system [67,68]	2024	O	Freiburg Germany	Dfb	Sh	L	Open–closed	Reinforced composite	T, DL	Real prototype		Aldrovanda vesiculosa Hindwing of insects	6
Kinetic Bimetal Module [42]	2024	---	---	---	Sh	T	Open–closed	Bimetal	T	Prototype	2D	Ammophila arenaria	3
Light-responsive kinetic façade system [41]	2023	O	Italy Naples	Csa	Reg	L	Expansion–contraction	Shape memory polymer	DL	Rhinoceros Grasshopper Ladybug Honeybee	3D	Gazania	3
Multifunction biomimetic adaptive building envelope (MBio-ABE) [17]	2023	O	Egypt New Cairo	BWh	Reg	T	Folding and rotation	Shape memory alloy photochromic glass	T	Energy Plus DesignBuilder	3D	Mimosa Pudica, Echinocatus grusonii, Lithops salicola	3
Dynamic solar shading system [44]	2022	O	---	---	Sh	S	Rotation	Coloured glass and transparent materials	DL	Rhinoceros Grasshopper Honeybee Ladybug Design Explorer	3D	Butterfly	3

Table 2. *Cont.*

Object	Year	Building Use	Country	Climate	Responsive Function	Environmental Trigger	Movement	Material	Analysis	Tools/Software	Surface	Organism of Inspiration	TRL
Biomimetic kinetic shading facade [69]	2021	O	Iran Yazd	BWh	Sh Reg	S	Curling	n/a	DL	Rhinoceros Grasshopper DIVA	3D	Tree	3
Bio-inspired interactive kinetic facade [43]	2021	O	Iran Yazd	BWh	Sh Reg	S	Elastic and deformable	n/a	DL	Rhinoceros Grasshopper DIVA	3D	Stomata	3
Biomimetic building envelope (bio-ABS) [70]	2020	E	Australia Sydney	Dfb	Sh Reg	S T	Expansion–contraction	Shape memory alloy (SMA) Photochromical	T	EnergyPlus	3D	Echinocatus grusonii	3
HygroSkin [55]	2013	Ex	France	Cfb	Reg	H	Open–closed	Wood	T	Real prototype	3D	Pine Cone	6

5. Discussion

5.1. Persistent Gap Between Research and Real-World Implementation

The evidence from both the bibliometric analysis and the state of the art review converges on a structural finding: despite growing theoretical maturity and increasing integration of biomimetics into computational design and optimisation processes, a marked discrepancy persists between the conceptual–prototypal level and the applicative level. The overwhelming majority of scientific production concentrates on simulation models, experimental demonstrators and prototypes, while cases of effective implementation on constructed buildings remain limited.

This gap is consistent with observations reported in existing reviews, which have similarly highlighted the concentration of biomimetic envelope research at conceptual and small-scale prototype stages. However, while existing reviews tend to derive this observation qualitatively from case selection [3,26], the present study grounds it in a cluster-guided, bibliometrically structured corpus of 2007 documents, providing a more systematic and replicable basis for this assessment. Notwithstanding the increase in scientific interest observable from 2013 onwards, the majority of solutions remain at the concept or small-scale prototype stage, with very few real-world large-scale applications documented [55,67]. The predominance of TRL 3 solutions identified in Table 2 quantitatively corroborates this observation, transforming what existing reviews have identified qualitatively into a measurable and comparable outcome across a systematically selected corpus.

This gap is particularly evident at the scale of the building envelope. Applications find greater, albeit predominantly experimental, traction in the field of biomimetic materials, where research focuses on multifunctional surfaces; bio-inspired composites; hygroscopic or thermoactive systems; and, more recently, intelligent and programmable materials. While these studies demonstrate significant potential in terms of passive regulation, adaptivity and energy reduction, they largely remain confined to laboratory prototypes or small-scale demonstrators, with limited transfer to current construction practice. A critical and recurrent methodological gap identified across existing reviews concerns the scarcity of mixed methods that integrate qualitative and quantitative approaches, that rigorously incorporate iterative feedback between biological theory and building performance analysis [26]. The bibliometric mapping presented in this study directly responds to this gap, offering a structured analytical bridge between the conceptual organisation of the field and the technological maturity of its outputs.

A further dimension of this gap concerns the temporal trajectory of the field. The overlay visualisation (Figure 3) reveals that the shift from morphological–structural emulation—copying biological forms for aesthetic or structural purposes—toward dynamic-functional emulation emerged bibliometrically in the most recent portion of the network, coinciding with the consolidation of Cluster C3 keywords (digital fabrication, additive manufacturing, and 4D printing) post-2018. Existing reviews have described this transition from morphological to dynamic-functional biomimicry as a fundamental evolution of the paradigm [71]; the present bibliometric analysis dates and spatialises this shift within the structure of the scientific literature, offering a quantitative counterpart to narrative accounts.

5.2. Economic Constraints and Barriers to Scale-Up

A further critical element, closely connected to the limited applicative diffusion of biomimetics in technical architecture, concerns the economic dimension. Costs associated both with the realisation of biomimetic interventions and, even more significantly, with the phases of research, prototyping and experimental validation represent a relevant barrier to large-scale implementation. Biomimetic solutions, particularly those integrating advanced materials, adaptive systems or digital fabrication technologies, frequently require non-standardised production processes, high levels of customisation and the employment of highly specialised competencies, resulting in cost increments relative to conventional building technologies.

This condition is particularly evident in the case of prototypes and experimental demonstrators, which constitute the current primary development domain of the discipline. The absence of economies of scale, combined with the lack of consolidated supply chains for many biomimetic materials and adaptive systems, contributes to maintaining high unit costs and limiting market transferability. Even in the few implemented cases, such solutions are typically associated with pilot projects or iconic buildings, where experimental or demonstrative value justifies above-average investment.

The lack of long-term testing data on material fatigue resistance and cyclic durability under real environmental conditions represents a further structural barrier, compounding economic constraints by preventing the accumulation of the performance evidence required for regulatory acceptance and insurance coverage [24].

Beyond economic barriers, a structural–functional bias emerges from the systematic analysis of Table 2, which reveals a marked concentration of solutions around solar shading and daylight regulation strategies. Existing reviews have identified a strong disproportion between the strategies studied: solar regulation and shading represent the most documented area, with a predominance of kinetic systems for visual and thermal comfort control, while energy harvesting and passive thermoregulation remain significantly under-researched, representing a critical gap for the achievement of net-zero objectives [70]. The present study quantitatively corroborates this observation: shading and regulation functions account for the dominant responsive strategy across all assessed cases, with thermal storage and energy conversion entirely absent from the reviewed corpus. This confirms a structural misalignment between the intrinsically multifunctional logic of biological systems and the predominantly mono-functional approach of current biomimetic envelope research. While nature operates through integrated, simultaneous responses to multiple environmental stimuli, most current systems adopt a single-challenge approach, addressing one environmental variable at a time.

This functional narrowing is compounded by a convergence around a limited set of enabling technologies. Smart materials have been identified as the key factor for eliminating mechanical complexity, enabling systems to respond directly to stimuli such as light, temperature and humidity without external energy consumption. The systematic review confirms this convergence: SMA, SMP and hygroscopic composites dominate the material column of Table 2, suggesting a partial consolidation of the technological toolkit despite the experimental nature of most applications. The limited penetration of these concepts into the broader architectural engineering literature—where terms such as "compliant mechanism" and "bistable" do not emerge as consolidated nodes in the VOSviewer network—may itself reflect a disciplinary blind spot, reinforcing the value of bibliometric mapping as a tool for detecting gaps that taxonomy-oriented reviews cannot easily identify.

From an architectural engineering perspective, this highlights a further gap between theoretical potential and practical application: while biomimetics offers highly efficient and promising models in terms of energy performance, adaptivity and resilience, their implementation still requires a process of technological and economic maturation enabling cost reduction, component standardisation and integration into existing construction supply chains. In this perspective, the economic sustainability of biomimetic solutions becomes as critical a factor as their performative efficacy.

5.3. Urban-Scale Biomimetics: A Largely Unexplored Frontier

Urban-scale biomimetics is based on the emulation of ecosystem functions to transform cities into regenerative systems capable of providing natural services such as air and water purification, climate regulation, and biodiversity support. This is achieved through methodological approaches such as Ecosystem Services Analysis (ESA), which defines quantitative objectives grounded in the site-specific ecological and climatic conditions and in comparisons with pre-development reference ecosystems; within this framework, the built environment integrates into natural processes, promoting ecological and social health and configuring buildings and infrastructure as interconnected nodes within a resilient urban system [21,22,72].

Operationally, the ESA-based approach can be structured in four sequential steps: (i) definition of a reference ecosystem, establishing the pre-development ecological baseline against which urban performance is assessed; (ii) identification of target ecosystem services to be restored or replicated; (iii) translation of these services into measurable urban performance variables (e.g., surface albedo, permeable area ratio, and evapotranspiration rate); and (iv) assessment through microclimate simulation, life-cycle assessment and ecosystem-services accounting. Applying this framework at the building-envelope level requires moving from envelope-component analogies to ecosystem-performance targets: the envelope findings reviewed in this article can inform urban-scale work only through careful upscaling. Solar-responsive shading concepts can contribute to district-level heat mitigation when coordinated with street orientation and urban-canyon geometry; hygroscopic or bio-based materials may support passive moisture buffering at component scale but require weathering and maintenance assessment before urban deployment; and digitally fabricated adaptive components may enable distributed responsiveness, yet they must be evaluated against robustness, accessibility and governance requirements. Therefore, the study treats urban biomimetics as an adjacent research frontier rather than as a direct extrapolation of façade-level results.

However, despite these conceptual advances, urban-scale biomimetics remains a largely unexplored frontier: bibliometric and thematic evidence indicates a marginal presence of studies systematically addressing this field. The future of the sector lies in the development of integrated solutions combining solar regulation with energy production and passive thermoregulation, moving beyond technology-driven, isolated approaches toward strategies that account for energy flows, material cycles, biodiversity and urban resilience simultaneously. Unlike at the building scale, the paradigm cannot be directly transposed by analogy but requires a shift in perspective toward an ecosystemic understanding of the city as a complex, adaptive, and interconnected system. The use of emerging technologies such as 4D printing, soft robotics and artificial intelligence, combined with low-carbon materials such as hygroscopic wood composites, has been identified as a promising pathway for transforming current biomimetic concepts into scalable and sustainable technologies. Nevertheless, such approaches remain largely theoretical and have yet to find a consolidated counterpart in widespread design practice, confirming that the transition from experimental demonstrators to deployable urban-scale systems represents the defining challenge for the next phase of biomimetic building research.

5.4. Limitations

The findings of this study should be read in light of several methodological choices. The use of Scopus provided a consistent and VOSviewer-compatible metadata structure, supporting the reproducibility of the bibliometric analysis. At the same time, it may have excluded relevant contributions indexed only in other databases, such as Web of Science, as well as design-oriented conference proceedings, books, and non-indexed architectural outputs.

Similarly, the three-block AND query was designed to construct a focused and reproducible corpus at the intersection of biomimicry, building envelopes, and performance-, material-, or fabrication-related research. However, this search strategy may not capture studies that address related themes without explicitly combining these terms in searchable fields. The resulting corpus should therefore be understood as a representative core of the indexed literature, rather than as a complete map of all work in the field.

The keyword co-occurrence analysis is also influenced by database indexing practices, keyword standardisation, and threshold settings. In this study, a minimum occurrence threshold of eight was selected to improve the readability of the network. This choice helped identify the dominant semantic structures of the literature but may have reduced the visibility of emerging interdisciplinary concepts, niche biological models, or novel design methods whose terminology is still unstable or infrequent. For this reason, the three VOSviewer clusters are interpreted as prevalent thematic patterns within the analysed corpus, not as fixed or exhaustive categories. This is especially relevant for frontier topics such as 4D printing, AI-assisted design, compliant mechanisms, programmable matter, and ecosystem-scale biomimetic design.

Finally, the TRL scores were inferred from the evidence reported in each selected article. They therefore assess the documented maturity of the analysed biomimetic envelope solutions, rather than the absolute market maturity of individual materials or components. Overall, these limitations define the interpretative boundaries of the study without undermining the main trends identified. To strengthen the robustness of the analysis, the bibliometric findings were triangulated with a cluster-guided qualitative review and a TRL assessment of selected envelope solutions.

6. Future Research Agenda

Based on the analysis conducted, and in light of the concentration of solutions at low Technology Readiness Levels, future research in biomimetic building envelopes should address a set of interrelated challenges across scales, materials and methodologies.

Component Scale: Materials and Adaptive Systems

At the component scale, a primary priority concerns the development and validation of advanced biomimetic materials under real climatic conditions. The transition from laboratory prototypes to field applications requires durability studies addressing cyclic hygric loading, ultraviolet degradation, thermal fatigue and mechanical wear. Particular attention should be directed to cellulose-based hygroscopic composites and SMA/SMP systems, among the most promising passive actuation technologies.

The potential of 4D printing deserves targeted research. The integration of programmable structures, bio-based materials and autonomous actuation aligns with the objectives of technical architecture in terms of reduced maintenance, embodied energy minimisation and scalability. Future work should focus on multi-material systems integrating hygroscopic, thermoactive and structural functions, as well as standardised testing protocols enabling cross-study comparison.

Envelope Scale: From Prototype to Deployable Systems

At the envelope scale, the main challenge is bridging the gap between experimental demonstrators and deployable building systems. This requires integration across material science, structural engineering, building physics and life-cycle assessment (LCA). Future research should develop performance frameworks assessing biomimetic envelopes not only in terms of energy and comfort, but across their full life cycle, from fabrication to end-of-life.

Regulatory integration is also critical. Current European standards do not adequately address adaptive biomimetic behaviours, particularly autonomous actuation, variable optical and thermal properties, and hygroscopic responses. The development of dedicated testing standards and performance metrics is therefore essential for adoption.

Urban Scale: Ecosystem-Level Biomimetics

At the urban scale, a theoretical and operational framework for ecosystem-based biomimetic design is needed, conceptualising the city as a complex adaptive system. Future research should operationalise this approach through urban metabolism models, nature-based strategies and multi-scale simulation workflows linking envelope behaviour to district-level energy and water dynamics.

Methodological Priorities: Biological Analogy Databases and AI-Assisted Transfer

A key cross-cutting priority concerns the systematisation of biological inspiration processes. The development of structured biological analogy databases, indexing natural systems by functional principles, stimuli-response mechanisms and material characteristics, would improve the translation between biology and design.

The integration of these databases with AI-assisted design tools and parametric environments represents a promising direction, enabling the exploration of bio-inspired design spaces and supporting multi-objective optimisation of envelope systems across energy, comfort and environmental performance criteria.

7. Conclusions

This study demonstrates that biomimetic approaches to climate-adaptive building envelopes are gaining increasing relevance yet remain predominantly confined to early-stage experimental development. By integrating bibliometric mapping, a cluster-guided literature review and a structured TRL assessment with explicit operational criteria, this study provides a systematic and quantitatively grounded characterisation of the field that existing narrative and taxonomy-oriented reviews have been unable to deliver.

- The bibliometric analysis of 2.007 Scopus documents identifies three principal thematic clusters—environmental-performative (C1), material-experimental (C2), and technological fabrication (C3)—and dates the disciplinary shift toward computational design and adaptive manufacturing to the post-2018 period. This temporal characterisation transforms a transition that existing reviews have described only narratively into a bibliometrically verifiable and spatially localised finding within the structure of the scientific literature.
- The cluster-guided review reveals a pronounced functional bias toward solar shading strategies, with energy harvesting and passive thermoregulation remaining critically underrepresented across the assessed corpus. This quantifies, on a systematically selected sample, a disproportion that existing reviews had identified qualitatively and confirms a structural misalignment between the intrinsically multifunctional logic of biological systems and the predominantly mono-functional approach of current biomimetic envelope research.
- The TRL assessment—conducted through a structured framework mapping each level to explicit validation criteria and applied here for the first time to a systematic corpus of biomimetic envelope solutions—reveals a clear concentration of solutions at low TRLs, highlighting a persistent gap between research exploration and real-world implementation. Over 80% of assessed solutions cluster at TRL 3, with only two cases reaching TRL 6 through sustained physical testing. This finding provides a measurable and comparable baseline against which future progress in the field can be tracked.

The convergence between bibliometric clusters and review findings confirms that the field is structured around three interrelated domains: environmental performance, technological processes, and material innovation. Within this framework, the building envelope is reaffirmed as a critical domain of architectural engineering, where environmental regulation, material behaviour and fabrication processes converge. Key barriers to implementation—including material fatigue and cyclic durability limitations, non-standardised production costs, and the absence of dedicated regulatory frameworks—are consistent across solution typologies, suggesting that overcoming them requires systemic rather than incremental interventions. Advancing beyond this experimental phase will require stronger integration across these domains, with particular emphasis on scalability, durability and system-level validation.

The findings suggest that the future advancement of biomimetic building envelopes will depend less on the discovery of new biological analogies and more on the technological maturation, validation, and industrial integration of existing concepts. In this perspective, the methodological framework proposed in this study—combining bibliometric mapping, a structured review and TRL assessment—offers a replicable model for monitoring the development trajectory of emerging technological fields in architectural engineering beyond the specific domain of biomimetic envelopes.

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