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Systematic Review

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Biomimetic Design in Architecture: A Systematic Review and Five-Dimensional Framework for Sustainable Building Performance

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Abstract

The built environment faces increasing pressure to reduce building energy demand and improve environmental performance in response to climate change, rapid urbanisation, and increasing thermal stress. Building façades play a critical role in mediating heat, light, moisture, and air exchange between indoor and outdoor environments. Biomimetic design provides an alternative approach by translating biological principles, processes, and adaptive mechanisms into architectural façade strategies. However, existing research remains fragmented on how biological principles translate into façade design and how these strategies influence building performance. This study therefore asks: How are biomimetic principles applied to building façades, and what performance outcomes are associated with these applications? We conducted a systematic review guided by PRISMA 2020; and qualitative thematic analysis using major academic databases. The search identified 109 relevant studies published between 2021 and 2026. The studies were analysed to identify recurring biological analogues, biomimetic design strategies, façade mechanisms, and reported performance outcomes. The synthesis identified five recurring dimensions of biomimetic application: nature as form, nature as process, nature as system, nature as material, and nature as adaptation. The reviewed evidence indicates that biomimetic façade strategies, including thermoregulatory systems, adaptive shading, hygroscopic materials, and bio-based materials, have been associated with improvements in thermal regulation, energy performance, and indoor environmental quality. These outcomes are primarily linked to passive environmental regulation, adaptive responsiveness, and the integration of façade behaviour with environmental conditions. The findings provide an evidence-based framework for understanding the translation of biological principles into façade design while highlighting the need for further empirical validation of their long-term energy performance, adaptability, durability, and practical implementation.

Keywords: biomimetic façades; adaptive building envelopes; building energy performance; climate-responsive architecture; sustainable building design

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1. Introduction

The biomimetic approach refers to the long-standing practice of using nature as a source of knowledge and guidance for addressing design challenges. Biomimicry is derived

from the Greek words bios (life) and mimesis (imitation), embodying the philosophy of learning from and emulating strategies observed in nature [1–3]. In the dynamic field of architecture, where creativity and functional requirements coexist, biomimicry provides a design approach that connects natural principles with the built environment [4,5]. By studying and translating the forms, processes, materials, and adaptive strategies of natural systems, architects can develop buildings that seek to combine aesthetic qualities with structural, environmental, and functional performance [3,6]. Fundamentally, biomimicry encourages architects to regard nature not merely as a source of visual inspiration but as a model for understanding how complex problems can be addressed through efficient biological strategies [1,7]. This involves identifying how natural organisms and systems respond to challenges such as heat regulation, resource use, structural efficiency, and environmental change and translating these principles into architectural design and construction [8,9]. For example, biomimetic approaches have been applied to adaptive solar envelopes, building shading systems, green façades, bio-inspired materials, and Climate-Responsive Building Technologies (CRBT) to improve energy and environmental performance [10–12]. Such approaches are particularly relevant to contemporary architecture because natural systems demonstrate strategies for efficient resource use, adaptation, resilience, and environmental responsiveness, which are increasingly important in the pursuit of sustainable and climate-responsive buildings [2,3,5]. Overall, biomimicry involves observing how natural systems address complex challenges and systematically translating these principles into architectural design, materials, building systems, and performance-oriented solutions [4,6].

Biomimicry in architecture (BA) encompasses multiple dimensions through which biological principles can be translated into architectural strategies to improve environmental performance, resource efficiency, resilience, and functional quality. The first dimension, nature as form, involves studying the morphology, geometry, patterns, and structural organisation of biological organisms and translating these characteristics into architectural forms and structural systems. Such approaches can contribute to lightweight construction, structural efficiency, material optimisation, and innovative building geometries [1,4]. The second dimension, nature as process, focuses on biological mechanisms and processes through which organisms regulate energy, heat, moisture, airflow, and resource flows. These principles can inform passive ventilation, thermal regulation, solar control, and other energy-efficient building strategies [6,8,9]. The third dimension, nature as system, emphasises the interconnected relationships among organisms, environmental conditions, and resource flows. In architectural applications, this perspective supports the integration of vegetation, water, airflow, energy, and ecological processes to enhance environmental performance and resilience [2,5]. A fourth dimension, nature as material, concerns the translation of biological material properties, structures, compositions, and production strategies into architectural materials and construction systems. Recent research demonstrates the potential of bio-inspired and bio-based materials to contribute to material efficiency, reduced environmental impacts, and low-carbon building applications [3,13,14]. The fifth dimension, nature as adaptation, focuses on the capacity of biological organisms and systems to respond dynamically to changing environmental conditions. This principle has informed adaptive façades, responsive solar envelopes, dynamic shading systems, and other CRBT designed to optimise performance under changing environmental conditions [8,11,12,15–17].

Collectively, these biomimetic dimensions offer important opportunities for improving architectural performance and sustainability. Biomimetic strategies can support energy and resource efficiency by translating biological mechanisms for regulating heat, airflow, water, and material use into building systems [3,6,10]. They can also contribute to climate responsiveness and resilience by enabling buildings to adapt to changing environmental conditions through responsive envelopes, shading systems, and other adaptive technologies [8,15]. At

the same time, biomimetic approaches can strengthen the relationship between buildings and their ecological contexts by integrating biological materials, vegetation, environmental processes, and resource cycles into architectural design [2,5]. Thus, biomimicry extends beyond the visual imitation of natural forms and represents a broader approach to learning from biological forms, processes, systems, materials, and adaptive strategies to develop more efficient, sustainable, and environmentally responsive architecture [15,18,19].

The aim of Biomimetic Façade Design (BFD) is to address architectural and environmental challenges by translating biological principles, processes, structures, materials, and adaptive mechanisms observed in nature into building-envelope solutions. Growing interest in biomimicry has been associated with the need to improve building efficiency, reduce environmental impacts, and develop architectural systems that respond more effectively to changing climatic conditions [2,4,6]. Biomimetic design can involve two complementary approaches: the solution-based or bottom-up approach, which begins with biological knowledge and explores its potential architectural application, and the problem-based or top-down approach, which starts from an architectural or engineering challenge and identifies analogous strategies in nature [6,8]. These approaches have supported developments in adaptive envelopes, shading systems, green façades, bio-inspired materials, and CRBT, although their application remains dependent on climatic, technological, and contextual conditions [9–11].

Biomimicry should also be distinguished from related concepts that are frequently used interchangeably in architectural discourse. Biomimetic design specifically involves the identification and translation of biological principles, functions, processes, materials, or systems into technological and architectural solutions [1,4]. This differs from broader nature-inspired design, bio-based materials, and approaches that primarily reproduce the visual characteristics of biological forms. The distinction is important because the presence of natural forms, biological materials, vegetation, or other nature-related features does not, by itself, establish a biomimetic design process. Rather, biomimicry requires an identifiable relationship between a biological principle and its architectural translation. Accordingly, this study focuses on how biological knowledge is translated into façade design and building-performance strategies, including form, process, system, material, and adaptive applications [20–22].

The relevance of biomimetic façades is particularly evident in relation to building energy performance and climate responsiveness [23,24]. As the interface between indoor and outdoor environments, the building envelope regulates important environmental exchanges, including solar radiation, heat transfer, daylight, moisture, and air movement. Consequently, façade configuration and performance can substantially influence building energy demand and indoor environmental conditions. Research on biomimetic building façades has demonstrated the potential of nature-inspired envelope strategies to improve energy performance across different building typologies and climatic conditions [3,25]. Similarly, recent research has examined adaptive solar building envelopes in relation to solar exposure, performance development, and design decision-making, demonstrating the growing emphasis on responsive façade systems [8]. Biomimetic shading skins have likewise been investigated as strategies for improving building energy efficiency through digitally optimised and nature-derived design solutions [9,17,25,26].

Nature provides numerous strategies for regulating heat, moisture, solar exposure, airflow, material performance, and resource use under changing environmental conditions. Biological organisms and systems respond to environmental pressures through mechanisms such as thermoregulation, self-shading, responsive movement, efficient resource utilisation, and material adaptation. These characteristics provide opportunities for translating biological functions into architectural technologies and environmental-control

strategies [1,6]. Recent studies illustrate this potential through plant-inspired adaptive façades, solar-responsive envelopes, microalgae-based façade systems, and biomimetic green façades designed to improve environmental and energy performance [10–12]. At a broader scale, biomimetic approaches can also draw upon relationships among organisms, resources, energy flows, and environmental processes, thereby extending the application of biomimicry from individual biological features towards integrated building and ecological systems [2,5]. These developments demonstrate that biomimicry can extend beyond the replication of natural appearance towards the systematic translation of biological functions, processes, materials, systems, and adaptive strategies into building technologies [27–29].

Conventional façade systems can provide insulation, solar control, weather protection, daylight regulation, and architectural expression, but many are based on relatively fixed configurations and therefore have limited capacity to respond dynamically to changing environmental conditions. Biomimetic façade strategies provide an alternative perspective by investigating how biological systems interact with and respond to environmental conditions and translating these principles into passive or adaptive architectural mechanisms [8,11]. Such approaches include responsive solar envelopes, adaptive shading systems, green façades, and biologically inspired material or surface strategies [9,10]. However, research remains distributed across architecture, building science, materials engineering, energy performance, and environmental technology. Although individual studies report promising applications, a broader synthesis is needed to clarify how particular biological principles are translated into façade strategies and how these strategies relate to measurable building-performance outcomes [4,6,17,22,25,27].

Although previous studies have reviewed aspects of biomimicry, building energy efficiency, adaptive façades, and nature-inspired building technologies, important gaps remain. Existing research often focuses on individual biological analogues, specific façade technologies, particular materials, or single performance indicators. For example, recent studies have addressed adaptive solar envelopes [8], biomimetic shading skins [9], green façades [10], and plant-inspired adaptive façade systems [11]. Other reviews have considered biomimetic building-energy strategies or broader applications of bionic architecture and low-carbon design [4,6]. Nevertheless, there remains limited systematic understanding of the relationships among biological principles, biomimetic dimensions, architectural strategies, façade mechanisms, and reported building-performance outcomes. The literature also varies substantially in terminology, methodological approach, climatic context, application scale, and performance indicators, making it difficult to identify recurring patterns across studies. A systematic synthesis is therefore needed to consolidate this fragmented evidence and establish a clearer conceptual structure for understanding biomimetic architectural applications.

The need for such a review is further reinforced by the practical challenges involved in translating biological knowledge into architectural systems. Biomimetic innovation frequently requires the integration of architectural design, engineering, biological knowledge, materials science, and building-performance analysis [1,3,7]. In addition, technological development, constructability, material availability, maintenance, scalability, and performance validation can influence whether biological principles can be successfully translated into practical building applications. Consequently, evidence of improved performance should not be inferred solely from the presence of biological inspiration. Biomimetic strategies require assessment against measurable outcomes, including energy performance, thermal conditions, environmental responsiveness, material efficiency, resource use, durability, and broader environmental impacts [3,5,15,18,19,30,31].

Although these perspectives provide complementary insights, their conceptual intersections can complicate the identification and comparison of predominant biomimetic

strategies across architectural studies. Another limitation concerns the relationship between biological inspiration, architectural translation, and measurable building performance. Biomimetic research encompasses conceptual proposals, computational simulations, laboratory experiments, material investigations, prototypes, and operational building applications. These approaches provide different levels of evidence regarding thermal regulation, energy efficiency, ventilation, daylighting, structural optimisation, resource conservation, and environmental responsiveness [3–6]. Consequently, performance outcomes established under simulated or controlled conditions cannot necessarily be generalised to operational buildings. Furthermore, implementation challenges involving initial investment, construction complexity, maintenance requirements, material durability, kinetic façade reliability, and technological scalability warrant consideration alongside reported environmental benefits. A synthesis that distinguishes conceptual potential from experimentally or operationally supported outcomes can therefore strengthen the interpretation of biomimetic architectural research.

To address these gaps, the present systematic review examines biomimetic architectural and building-envelope applications published between 2021 and 2026 through an integrated five-dimensional framework comprising nature as form, process, system, material, and adaptation. Rather than introducing entirely new biomimetic concepts, the framework consolidates established classification perspectives into an architecture-oriented analytical structure with clearer operational boundaries. It distinguishes morphological translation from biological processes, individual mechanisms from interconnected systems, intrinsic material properties from broader architectural applications, and passive responsiveness from actively controlled adaptation. These distinctions support the identification of predominant biomimetic strategies while recognising that individual applications may incorporate multiple dimensions.

The study contributes by systematically organising heterogeneous research findings, relating the five dimensions to relevant building-performance objectives, and distinguishing conceptual overlap from the primary classifications used in descriptive frequency analysis. By examining the nature and limitations of reported evidence, the review also provides a basis for identifying implementation challenges and future research priorities. Accordingly, the proposed framework is presented as a complementary analytical approach for interpreting biomimetic architectural applications rather than a replacement for existing classifications or an independently validated performance-prediction model.

Guided by PRISMA 2020 principles and supported by qualitative thematic coding and descriptive synthesis, the review identifies recurring biological principles, architectural strategies, applications, performance objectives, and reported outcomes. The study develops an evidence-based framework that organises the reviewed literature into five complementary dimensions. The synthesis subsequently examines how these dimensions are translated into architectural strategies and how they relate to structural efficiency, energy and resource optimisation, ecological integration, material sustainability, and environmental adaptation. In doing so, the review provides a structured basis for understanding the evolution of biomimetic architectural design and identifying research gaps and opportunities for future development.

This study aims to systematically synthesise the existing literature on biomimetic architectural design, identify the principal strategies through which biological principles are translated into architectural applications, and develop an evidence-based five-dimensional framework. The study further compares representative architectural case studies to examine how these dimensions contribute to structural, environmental, material, ecological, and adaptive building performance.

Specifically, the study answers the following research questions:

RQ1: What are the principal biomimetic strategies reported in the literature on architectural and building design?

RQ2: How can the identified biomimetic strategies be systematically classified according to the biological principles and architectural functions they emulate?

RQ3: How do the identified biomimetic dimensions contribute to building performance in terms of structural efficiency, energy and resource optimisation, ecological integration, material sustainability, and environmental adaptation?

RQ4: What patterns, gaps, and future research directions emerge from the application of biomimetic principles in architectural design?

This study underscores the potential of biomimetic principles in transforming façade design to achieve enhanced energy efficiency, sustainability, and occupant well-being. By leveraging nature's adaptive strategies, biomimetic façades can address the limitations of conventional systems, reducing energy consumption and promoting environmentally conscious architecture. The integration of biomimicry into practical façade solutions offers a pathway toward more sustainable and adaptive building practices, bridging the gap between biological paradigms and contemporary architectural needs. The findings of this study have significant implications for sustainable architecture and energy-efficient building practices. Architects, engineers, and policymakers can utilise biomimetic principles to create self-regulating façades that align with global sustainability goals. Moreover, the study highlights the need for interdisciplinary collaboration and technological innovation to address the challenges of implementing biomimetic designs in practical, scalable ways. Regulatory frameworks will also need to evolve to support the adoption of such innovative solutions [20,22,32].

2. Materials and Methods

The reporting of this review was checked against the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) checklist (Supplementary Table S1).

It outlines 27 reporting items covering compliance with established systematic review reporting guidelines. In addition, Supplementary Table S2 presents the PRISMA 2020 Eligibility and Verification Assessment of Reference Entries (Years 2021 and 2026 periods). These checklist documents address each applicable reporting item and identify items requiring confirmation from the original review records. Guided by the PRISMA framework, this study investigates the application of biomimetic principles in architectural and building design. The review focuses on identifying, classifying, and synthesising how biological knowledge is translated into architectural strategies and how these strategies relate to building performance, sustainability, environmental responsiveness, and adaptation. The PRISMA-guided approach was adopted to support a transparent, structured, and reproducible process of literature identification, screening, eligibility assessment, data extraction, and inclusion [33,34]. The eligibility/verification column systematically assesses the 109 bibliographic entries identified in the review based on their relevance to biomimetic architectural design, publication period (2021–2026), methodological characteristics, and alignment with the predefined inclusion and exclusion criteria. Each reference was provisionally classified according to its potential eligibility, the need for further verification, or its role as supporting methodological or contextual literature. Particular attention was given to identifying duplicate records and publications outside the review's scope. This assessment enhances transparency, supports the reconciliation of included studies, and provides a structured basis for final eligibility confirmation in accordance with PRISMA 2020 reporting principles [33,34]. The screening process therefore ensured that the final evidence base was sufficiently focused on biomimetic applications and their implications for architectural and

building performance. Supporting classification and synthesis of biomimetic strategies and their architectural applications [20–23] were analysed.

The review consolidates evidence from the selected literature to identify recurring biological principles, biomimetic strategies, architectural applications, performance objectives, and reported outcomes [23–26]. Particular attention is given to the relationships between biological inspiration and architectural translation, including the ways in which natural forms, processes, systems, materials, and adaptive mechanisms are incorporated into building design. The methodological procedure therefore combines systematic literature identification and screening with structured data extraction, thematic coding, and descriptive synthesis. Given the methodological and outcome heterogeneity of the included studies, the synthesis emphasises thematic and descriptive comparison rather than statistical meta-analysis. The review ultimately uses the synthesised evidence to develop a five-dimensional framework comprising nature as form, nature as process, nature as system, nature as material, and nature as adaptation, providing an evidence-based structure for understanding the development and performance implications of biomimetic architectural design. This study's framework (Figure 1) emphasises the complementary and overlapping relationships among the five dimensions and follows the analytical pathway from biological principle and abstraction to architectural translation, performance mechanism, and building outcome.



Figure 1. Study's framework illustrating the translation of five-dimensional biomimetic architectural applications and performance outcomes adaptation. Source: Author's Conceptualisation.

2.1. Literature Search and Coding

A comprehensive and structured literature search was conducted to identify recent research on biomimetic architecture, building envelopes, adaptive façade systems, biological thermoregulation, nature-inspired environmental regulation, and the associated energy and environmental performance of biomimetic building technologies. The search was conducted across major academic databases, including Scopus, Web of Science, and ScienceDirect, while Google Scholar was used as a supplementary source to identify additional relevant publications and potentially overlooked studies. Boolean operators and combinations of keywords were developed to capture the multidisciplinary nature of biomimetic façade research. Representative search strings included "biomimicry AND architecture," "biomimetic design AND building," "biomimetic façade AND building envelope," "adaptive façade AND biomimicry," "responsive façade AND nature-inspired design," "biological thermoregulation AND architecture," "plant-inspired shading AND building," "nature-inspired ventilation AND architecture," "hygroscopic material AND building façade," "bio-based materials AND building performance," "kinetic façade AND energy efficiency," "passive cooling AND termite mound," "biomimetic design AND thermal performance," and "biomimicry AND life-cycle assessment." This broader search strategy was adopted to ensure that the review captured not only conceptual applications of biomimicry but also technologically developed and performance-oriented façade strategies.

The literature search was restricted to publications published between 2021 and 2026 to capture recent developments in biomimetic architectural design and the increasing emphasis on translating biological knowledge into performance-oriented building applications. This period encompasses recent advances in adaptive and responsive façades, computational and digitally optimised design, bio-inspired materials, environmental technologies, and building-performance assessment [6,8,9,30]. The selected timeframe also captures emerging applications addressing energy efficiency, thermal regulation, climate responsiveness, material sustainability, carbon reduction, and broader environmental performance [3,5,10,11].

The review considered the conceptual diversity of biomimetic applications and did not restrict biomimicry to the visual replication of biological forms. Existing literature demonstrates that biological knowledge can be translated through different levels and aspects, including organism characteristics, behavioural processes, ecosystem relationships, biological materials, functional mechanisms, and adaptive responses [1,4]. Accordingly, the data-extraction and coding procedure examined whether each study translated biological morphology, functional mechanisms, material properties, processes, systemic relationships, or adaptive responses into architectural or building-performance strategies. This approach enabled the identification of recurring patterns across otherwise diverse applications, including building form, environmental control, materials, ecological integration, and adaptive building systems [22,32,35].

The five-dimensional framework developed in this study was not imposed as a predetermined classification during the initial literature assessment. Instead, the dimensions emerged through the thematic coding and subsequent consolidation of recurring patterns across the included studies. The identified dimensions nature as form, nature as process, nature as system, nature as material, and nature as adaptation therefore represent an evidence-based synthesis of how biological principles are translated into architectural applications. Because individual studies may incorporate more than one biological principle or architectural strategy, the dimensions are treated as complementary and potentially overlapping rather than mutually exclusive. This coding approach enables the review to move beyond a simple catalogue of nature-inspired examples and provides a structured basis for examining the relationships between biological principles, architectural translation, and building-performance outcomes.

Relating to eligibility, clear inclusion and exclusion criteria were established to ensure the quality, consistency, and relevance of the selected studies. Inclusion criteria covered peer-reviewed journal articles and conference papers published in English that addressed biomimicry or bio-inspired strategies in architecture, building envelopes, façade systems, building materials, or the wider built environment. Priority was given to studies providing empirical evidence, simulation results, experimental investigations, monitored case studies, material testing, or documented architectural applications. Studies addressing adaptive and responsive façades, biological thermoregulation, plant-inspired shading or ventilation, hygroscopic or bio-based materials, kinetic façade systems, passive environmental regulation, building energy performance, and environmental or life-cycle performance were included where they demonstrated a clear connection with biomimetic principles. Studies were excluded when they were purely biological without an architectural or technological application, focused exclusively on unrelated engineering fields, lacked sufficient methodological information, or consisted primarily of editorials, opinion pieces, or non-evidence-based commentary. These criteria were applied to improve the methodological consistency and relevance of the evidence base [36,37].

A systematic screening and selection process was applied following the PRISMA 2020 guidelines to identify and screen studies for this review [34]. A total of 285 records were identified by searching four different databases, including Scopus ($n = 90$), Web of Science ($n = 65$), ScienceDirect ($n = 52$), and Google Scholar ($n = 78$). After removing 117 duplicates, 168 records remained for screening at the title and abstract level. Consequently, 52 records were excluded at this level due to being irrelevant to biomimetic architecture ($n = 28$), a lack of a specific focus on building envelopes or materials ($n = 14$), being a review, an editorial note, or a conference abstract ($n = 7$), or a non-architectural context ($n = 3$). As a result, 116 reports were fetched for full-text screening, all of which were retrieved and assessed. Seven articles were excluded on the full-text screening due to being irrelevant to biomimetic materials and technologies ($n = 4$), published before 2021 or after 2026 ($n = 2$), or providing insufficient information for this review ($n = 65$). Eventually, 109 studies were included in the final qualitative thematic analysis and evidence synthesis. The selection process is summarised in Figure 2, illustrating the identification, screening, eligibility, and inclusion processes of this systematic literature search and screening in accordance with the PRISMA 2020 guidelines.

2.2. Data Extraction and Coding Framework

A structured data-extraction framework was developed to ensure consistency, transparency, and reproducibility in the synthesis of the included literature. The framework was designed in accordance with the objectives and research questions of the review and was used to systematically record bibliographic characteristics, geographical context, methodological features, biological principles, architectural applications, biomimetic dimensions, and reported performance outcomes. This approach is consistent with PRISMA 2020 recommendations concerning the definition and reporting of data items and with established guidance for data extraction in systematic and scoping reviews. Supplementary Table S3 presents the twelve principal data fields that were extracted, namely (i) author and year, (ii) country, (iii) study type, (iv) biological organism or system, (v) biological principle, (vi) biomimetic level, (vii) architectural application, (viii) biomimetic dimension, (ix) performance objective, (x) reported outcome, (xi) case study or building, and (xii) validation method. These fields were selected to establish a consistent analytical link between the biological source of inspiration, its abstraction into a design strategy, its architectural application, and the resulting performance implications.

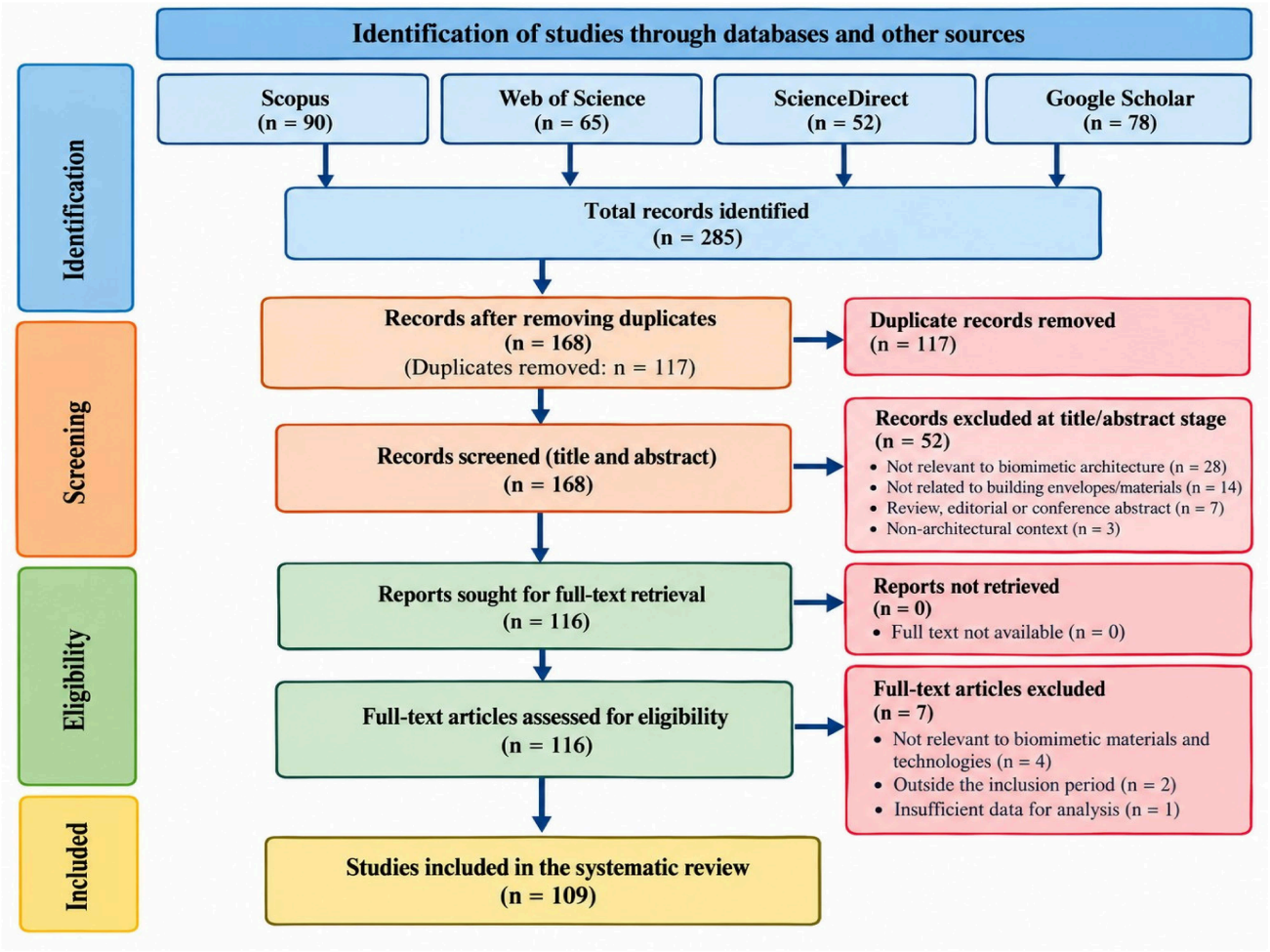


Figure 2. PRISMA 2020 guideline for the article identification and selection process.

Author and year recorded the bibliographic identity and publication period of each study, enabling the temporal development of biomimetic architectural research to be examined. Country identified the geographical context in which the study was conducted or the principal case study was located. Study type captured the methodological character of each contribution, such as conceptual study, case study, simulation/model-based investigation, experimental study, empirical research, design research, or review. The biological characteristics of each study were captured through three related fields. Biological organism or system identified the organism, biological structure, natural phenomenon, or ecological system that provided the source of inspiration. Biological principle recorded the specific characteristic, mechanism, behaviour, structural property, process, or ecological relationship abstracted from nature [38]. Biomimetic level identified the level at which biological knowledge was translated into architecture, distinguishing, where applicable, between organism-, behaviour/process-, and ecosystem/system-level biomimicry. This distinction enabled the review to differentiate between imitation of biological form and the emulation of biological functions, processes, interactions, and adaptive behaviour.

The architectural translation of the biological principle was recorded through architectural application, which identified the principal building component, spatial strategy, structural system, material, façade, environmental-control system, landscape intervention, or broader architectural configuration in which biomimicry was applied. The systematic literature review and the illustrative architectural case examples were treated as distinct components of the research methodology. The 109 included publications formed the primary evidence base for the qualitative thematic synthesis and development of the five-dimensional

biomimetic design framework. In contrast, selected architectural projects, including the Eden Project, Turning Torso, Eastgate Centre, Al Bahar Towers, and Bosco Verticale, were presented as supplementary illustrations of nature-inspired design principles in architectural practice. Each study was assigned one or more biomimetic dimensions based on the five-dimensional framework developed through the thematic synthesis: nature as form, nature as process, nature as system, nature as material, and nature as adaptation.

The coding of biomimetic dimensions was deliberately treated as non-mutually exclusive. A study could therefore be assigned to more than one dimension where its architectural strategy incorporated multiple biological principles. For example, an adaptive façade may simultaneously employ a biological form, emulate a natural process, and demonstrate environmental adaptation. Consequently, the five dimensions of biomimetic design are conceptually non-mutually exclusive, as individual studies may incorporate multiple biological principles and design strategies. However, for the descriptive frequency analysis, each of the 109 included studies was assigned to one predominant dimension based on its primary research focus and principal biomimetic application. Accordingly, the reported frequencies (33, 23, 20, 18, and 15) sum to 109 and represent mutually exclusive primary classifications rather than the complete occurrence of each dimension across the reviewed literature. Although conceptual overlap is recognised within the proposed framework, the present frequency distribution does not quantify secondary dimensional associations.

The final four fields focused on architectural performance and empirical support. Performance objective recorded the principal purpose of the biomimetic intervention, including structural efficiency, energy efficiency, thermal comfort, resource conservation, ecological integration, material sustainability, resilience, or climate adaptation. Reported outcome captured the principal performance result or qualitative finding reported by the study, including reductions in energy or material use, improvements in thermal or environmental performance, enhanced structural efficiency, ecological benefits, or increased adaptability. Case study or building identified the architectural project, building, urban intervention, prototype, or experimental application used to demonstrate the biomimetic strategy as supported by previous studies [39]. Finally, validation method recorded how the reported findings were supported, including comparative analysis, expert assessment, or qualitative case-study evaluation. In the present study, however, case studies were used primarily to contextualise and illustrate patterns identified through the systematic literature synthesis rather than as a substitute for the systematic-review evidence.

The data-extraction process followed a standardised and iterative procedure. Initially, the data-extraction framework was developed and pilot-tested on a subset of the included studies to identify ambiguities, overlaps, and inconsistencies in the coding categories. The framework was subsequently refined before being applied to the complete dataset. This iterative approach is consistent with established evidence-synthesis practices, in which extraction and coding frameworks are refined to improve consistency and transparency during the review process [33,40]. Information was extracted primarily from the full texts of the included studies, with supplementary information obtained from tables, figures, appendices, and methodological descriptions where necessary. Where a study contained insufficient information for a particular field, the field was recorded as "not reported" rather than inferred, thereby reducing the risk of introducing unsupported interpretations into the dataset [20,29,31].

Following extraction, the coded data were subjected to a two-stage analytical process. First, descriptive analysis was used to identify patterns in publication characteristics, geographical distribution, study types, biological sources, architectural applications, and performance objectives. Second, thematic coding was used to consolidate recurring biological and architectural strategies into the five higher-order biomimetic dimensions: nature

as form, nature as process, nature as system, nature as material, and nature as adaptation. The coded dimensions were subsequently compared with reported performance objectives and outcomes to examine how different forms of biological inspiration were translated into architectural strategies and associated performance considerations. This combination of descriptive and thematic synthesis is appropriate for heterogeneous literature in which studies differ in research design, application, biological inspiration, and reported outcomes [41,42].

Supplementary Table S4 presents the structured phases of the thematic analysis adopted in this study to classify biomimetic design principles. It outlines the progression from data familiarisation and initial coding to theme development, refinement, and final interpretation. The procedure was informed by established principles of thematic analysis, particularly the iterative movement between coded data, candidate themes, and the broader evidence base [43]. However, the five dimensions identified in this study were not treated as predetermined themes. Rather, they emerged through iterative comparison and consolidation of the coded evidence and were subsequently interpreted in relation to established biomimicry classifications and architectural applications [4–6]. This approach provides a transparent link between the extracted evidence and the development of the five core biomimetic dimensions presented in the subsequent analysis.

2.3. Data Analysis and Thematic Synthesis

The extracted data were analysed using a structured qualitative thematic analysis approach to identify recurring patterns, relationships, and conceptual categories across the selected studies [43,44]. Given the substantial heterogeneity of the reviewed literature in terms of research designs, building types, climatic contexts, biomimetic principles, façade technologies, and performance indicators, statistical meta-analysis was not considered appropriate. Instead, the review employed a systematic qualitative synthesis supported by structured descriptive comparison of the reported evidence. This approach enabled the findings to be compared across studies while preserving differences in methodological design and contextual conditions.

The thematic analysis followed a systematic sequence of data familiarisation, initial coding, categorisation, theme development, review, and refinement, consistent with contemporary guidance for rigorous qualitative synthesis [43]. Following full-text screening, relevant information was extracted using a standardised coding framework. Each study was coded according to its publication characteristics, biological analogue or inspiration, biomimetic principle, level of biological-to-architectural translation, façade or building application, technological or material strategy, environmental context, research method, and reported performance outcomes. Performance-related evidence was further coded according to thermal regulation, energy performance, thermal comfort, daylighting, ventilation, moisture regulation, indoor environmental quality, material efficiency, carbon implications, and broader sustainability outcomes. These projects were selected for their relevance to biomimetic form generation, environmental responsiveness, adaptive building systems, and the integration of natural principles into architectural design. Where individual projects were discussed within publications included in the systematic review, their interpretation was informed by those sources. However, the projects themselves were not counted as separate studies, and supplementary project descriptions were not incorporated into the systematic evidence totals.

A two-stage thematic coding procedure was employed. First, the biological inspiration and architectural application reported in each study were extracted and coded inductively. Second, recurring patterns were consolidated into five higher-order analytical dimensions: nature as form, nature as process, nature as system, nature as material, and nature as adaptation. This approach reflects the conceptual diversity of biomimicry research, which

distinguishes applications according to biological morphology, function, process, material properties, behavioural mechanisms, and ecosystem relationships [4–6]. Studies could receive multiple codes where their biomimetic strategies incorporated more than one dimension, recognising that biomimetic architectural interventions may operate simultaneously across different biological levels and modes of translation [1,3]. Frequencies were subsequently calculated to identify the relative representation of each dimension across the reviewed literature.

The coding process was designed to distinguish between different levels of evidence, including conceptual proposals, laboratory or material experiments, numerical simulations, prototypes, monitored buildings, and documented case studies. This distinction was important for avoiding the assumption that all reported biomimetic strategies had equivalent empirical support. Where studies reported quantitative performance indicators, such as energy consumption, cooling demand, temperature reduction, thermal comfort, or daylight performance, these findings were recorded and comparatively examined. The initial coding generated a set of recurring concepts that were subsequently compared, consolidated, and refined into five dominant thematic dimensions. These themes were not treated as predetermined categories; rather, they emerged through iterative comparison of the coded evidence and were subsequently examined against classifications and conceptual approaches identified in the existing biomimicry literature [2,4–6]. The resulting five dimensions provide an architecture-focused analytical structure for examining how biological characteristics, processes, systems, materials, and adaptive behaviours are translated into architectural and façade applications. In particular, recent research on adaptive envelopes, bio-inspired façades, and climate-responsive architecture supports the relevance of distinguishing adaptive responses as a specific dimension of contemporary biomimetic design [8,9,11].

A comparative synthesis was subsequently undertaken to examine the relationships among each biomimetic dimension, the biological principle being translated, the corresponding architectural strategy, and the reported building-performance outcome. Particular attention was given to strategies involving thermoregulation, passive cooling and ventilation, adaptive shading, responsive building envelopes, bio-based and biomimetic materials, ecological integration, and other nature-inspired approaches [2,5,6,15]. The comparison considered both the reported benefits and the contextual conditions under which these outcomes were observed, including climatic conditions, building type, design application, and methods of performance assessment. This contextual approach is important because the performance of biomimetic strategies depends on their biological principle, architectural translation, environmental conditions, and method of validation rather than on biomimicry alone [3,4]. The synthesis therefore focused on identifying areas of convergence and variation across the reviewed studies rather than assuming that biomimetic strategies produce uniform performance benefits across different contexts [45–48].

A structured comparative assessment was further undertaken to examine reported contributions to feasibility, environmental responsiveness, resource efficiency, and sustainability across different climatic and environmental contexts. Where quantitative performance results were available, these were retained as reported by the original studies and used to support descriptive cross-study comparison. Evidence derived from conceptual proposals, numerical simulations, laboratory experiments, prototypes, and monitored or experimentally validated applications was distinguished during the synthesis to reflect differences in evidential strength. This distinction was particularly important when interpreting claims concerning energy efficiency, thermal performance, material sustainability, ecological integration, and adaptive building performance. Recent studies on biomimetic façades, adaptive solar envelopes, and bio-inspired materials demonstrate the importance of combining bio-

logical abstraction with measurable performance assessment, simulation, experimentation, or other forms of validation [8,9,11].

Overall, the analytical procedure combined systematic evidence extraction, thematic coding, qualitative synthesis, and descriptive cross-study comparison. The resulting analytical framework establishes a traceable relationship between biological principle, biomimetic dimension, architectural strategy, performance mechanism, and building outcome. This structure enabled the reviewed studies to be interpreted according to the five dimensions identified through the thematic synthesis: nature as form, nature as process, nature as system, nature as material, and nature as adaptation. The five dimensions are consistent with the broader literature, which identifies biological form, processes, materials, functions, behaviours, and ecosystem relationships as important pathways for transferring knowledge from nature into architectural applications [4–6,49]. Because individual studies may incorporate more than one dimension, the coding framework allowed overlapping classifications where multiple biological principles or architectural strategies were evident. The methodology therefore recognises the heterogeneity of the reviewed evidence and differences in validation approaches, avoiding unsupported generalisations regarding the effectiveness of biomimetic design while providing a structured basis for understanding its potential contribution to sustainable, resilient, and climate-responsive architecture [2,3].

2.4. Classification of Architectural Applications and Stratified Analysis

To differentiate the conceptual dimensions of biomimetic design from their architectural applications, an additional level of application was established based on the approaches described by previous biomimetic architectural reviews [1,2,4,6]. The five categories of building façades and envelopes, building materials, structural systems, integrated building and environmental systems, and building-related ecological applications are based on approaches previously discussed in the literature [1,3–6] and as presented in the Supplementary Table S5. The five-dimensional framework of biomimetic design highlights the dominant biological principle behind a strategy, whereas the application level is the architectural component or system to which a strategy is applied. This distinction is analogous to research on the translation of biological principles into morphological forms, mechanistic functions, novel materials, and environmental strategies [1,3–6].

Studies addressing building-envelope technologies, such as adaptive shading systems, passive ventilation, solar control, thermoregulation, and environmental responsiveness, fall under the façade-related category [8–11]. Building materials include bio-inspired composites, hierarchical structures, self-healing materials, and responsive construction materials [2,4,5]. Structural applications comprise nature-inspired geometries, load-bearing configurations, and optimisation strategies derived from biological systems [1,4]. Integrated building and environmental systems include coordinated energy regulation, water management, resource efficiency, and environmental-control mechanisms [4–6]. Building-related ecological applications pertain to ecosystem-inspired interventions associated with architecture, building-integrated vegetation, ecological resource cycles, and environmental performance [1,5,10,12].

Studies addressing landscape or ecological systems not specifically associated with an architectural or building-performance application have been excluded from the review scope. This eligibility distinction reflects the architectural focus of the study and facilitates a more consistent interpretation of biomimetic strategies relevant to different building components and environmental contexts [2–4]. These proposed classifications enable the differentiation of façade-specific findings from those related to other architectural applications, reducing the overgeneralisation of performance outcomes between building systems. The application categories are distinct from the five biomimetic dimensions.

When studies address multiple building components, secondary application categories can be added; however, descriptive frequencies based on predominant applications are distinguished from multiple-response counts. Stratified findings are interpreted using information available at the study level, including research methods, validation strategies, climatic contexts, and performance indicators reported [3–6,8]. This approach allows a structured comparison between façade and non-façade applications, considering their varying technological characteristics, implementation contexts, and evidential support.

3. Results and Discussion

3.1. Descriptive Characteristics of the Included Studies

A systematic screening and descriptive analysis were conducted in accordance with PRISMA 2020 guidelines to identify, evaluate, and characterise the relevant literature [33,34]. The selection process involved duplicate removal, title and abstract screening, and full-text eligibility assessment based on predefined inclusion and exclusion criteria. Six reviewers participated in evaluating the methodological suitability, thematic relevance, and contributions of the retrieved studies to biomimetic architectural design and sustainable building performance. Following the screening and eligibility assessment, 109 studies published between 2021 and 2026 were retained for the final qualitative synthesis.

The included studies were systematically characterised according to publication year, geographical distribution, research methodology, façade strategies, biological analogues, building typologies, climatic contexts, and reported performance indicators. Since individual studies frequently addressed multiple façade strategies, biological analogues, building types, or performance indicators, these variables were independently coded, allowing overlapping classifications where applicable. The temporal distribution presented in Table 1 indicates a generally increasing research interest throughout the review period, with a greater concentration of publications in the later years. This trend reflects growing scholarly attention to translating biomimetic principles into measurable architectural performance improvements, particularly through adaptive and responsive façades, passive environmental regulation, innovative materials, and energy-efficient building envelopes. Collectively, these developments highlight the increasing relevance of performance-oriented biomimetic approaches in advancing sustainable architectural design.

Table 1. Publications between 2021 and 2026 (n = 109).

Publication Year	Number of Studies	Percentage (%)
2021	9	8.3
2022	14	12.8
2023	18	16.5
2024	21	19.3
2025	25	22.9
2026	22	20.2
Total	**109**	**100.0**

Potential sources of heterogeneity among the 109 included studies were explored by means of descriptive comparison of subgroups and qualitative thematic synthesis. The studies were categorised according to geographical distribution, research methodology, architectural application, façade strategy, biological analogue, building typology, climatic context, and reported performance indicators. This allowed for assessing differences in research approaches, biomimetic applications and sustainability outcomes in relation to the studied variables. Due to the methodological diversity and differences in outcome variables reported by the authors, a quantitative aggregation of results such as a meta-analysis or a

meta-regression was not performed. Instead, heterogeneity was qualitatively explored to identify patterns and trends in biomimicry research.

The study employed qualitative thematic synthesis supported by descriptive frequency analysis to systematically examine and classify the findings of the included studies. As no quantitative meta-analysis or pooled effect-size estimation was undertaken, conventional statistical sensitivity analyses were not applicable, and the robustness of the synthesised findings was not independently assessed through formal sensitivity testing. Nevertheless, the findings were interpreted with consideration of methodological variations, architectural applications, climatic contexts, biological analogues, and reported building-performance indicators. The proposed five-dimensional framework served as an analytical structure for organising and interpreting the available evidence rather than establishing causal relationships or estimating the quantitative effectiveness of biomimetic interventions. Accordingly, the reported frequencies and thematic patterns represent descriptive characteristics of the reviewed literature and should be interpreted in light of differences in study design, evidence quality, and application context. The absence of formal sensitivity analyses, particularly those examining alternative classification decisions or study-exclusion criteria, is acknowledged as a methodological limitation that may influence the robustness and generalisability of the synthesised findings.

The potential influence of reporting biases was taken into account while interpreting the findings of the systematic review. Due to the qualitative nature of the analysis, no formal statistical evaluation of reporting bias was performed as the review did not involve meta-analysis. Nonetheless, the synthesis acknowledged that selective outcome reporting and publication bias could contribute to an overrepresentation of positive findings related to energy efficiency, thermal performance, environmental adaptation, and sustainability benefits of biomimetic building approaches. Therefore, the reported performance outcomes were interpreted with caution, taking into consideration the variations in methodologies, applications, validation strategies, and the availability of performance evidence across the included studies. Acknowledging the lack of a formal assessment of reporting bias is considered a limitation of the present research.

Given the methodological heterogeneity of the included studies, no formal evidence-certainty assessment framework, such as GRADE, was applied. Nevertheless, the findings were interpreted by considering research methodologies, validation approaches, architectural applications, climatic contexts, and reported performance indicators. The synthesis also distinguished evidence derived from conceptual investigations, computational simulations, experimental studies, and operational building applications, thereby supporting a more transparent and balanced interpretation of the findings without assigning unsupported certainty ratings or making definitive claims regarding intervention effectiveness.

The descriptive synthesis of 109 included studies revealed five dimensions of biomimetic advancement in architectural applications: nature as adaptation, nature as form, nature as process, nature as system, and nature as material (Figure 3). Nature as adaptation was the most common strategy reported across 33 of 109 (30.3%) studies. Following closely was nature as form in 23 of 109 (21.1%) studies. The application of BA as a process was present in 20 of 109 (18.3%) studies, whereas nature as a system accounted for 18 of 109 (16.5%) studies. Finally, the biomimetic architectural application in terms of material was reported in 15 of 109 (13.8%). In general, the findings suggest that biomimetic architectural research is more focused on adaptation and form than material.

The geographical analysis (Figure 4) indicates that biomimetic façade research is distributed across several climatic and regional contexts, although studies are concentrated in Asia and Europe. The geographical classification refers to the primary location or case-study context investigated in each publication. The distribution demonstrates that biomimetic

façade research is being undertaken across diverse environmental settings, including hot-arid, hot-humid, temperate, Mediterranean, and cold climates. However, the comparatively smaller number of studies from Africa and Latin America indicates an opportunity for further investigation of biomimetic façade applications in underrepresented climatic and socioeconomic contexts.

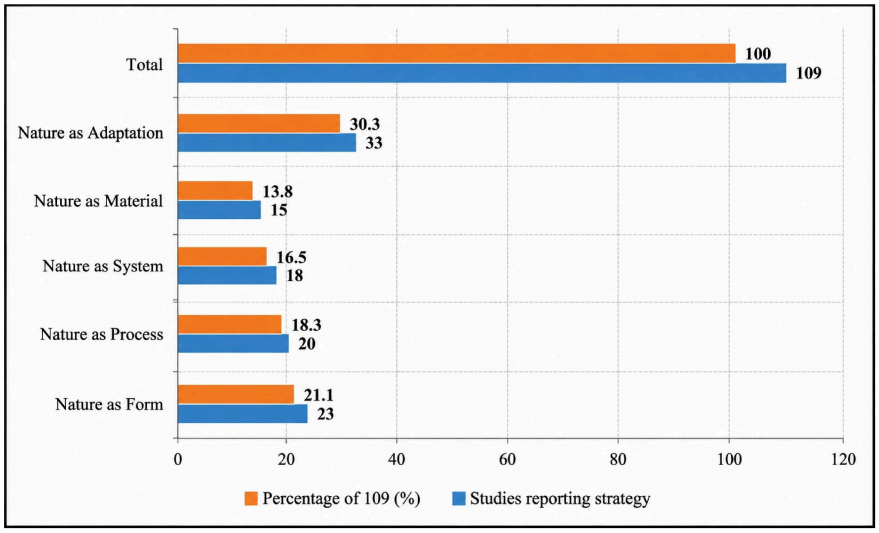


Figure 3. Advancements in biomimetic design.

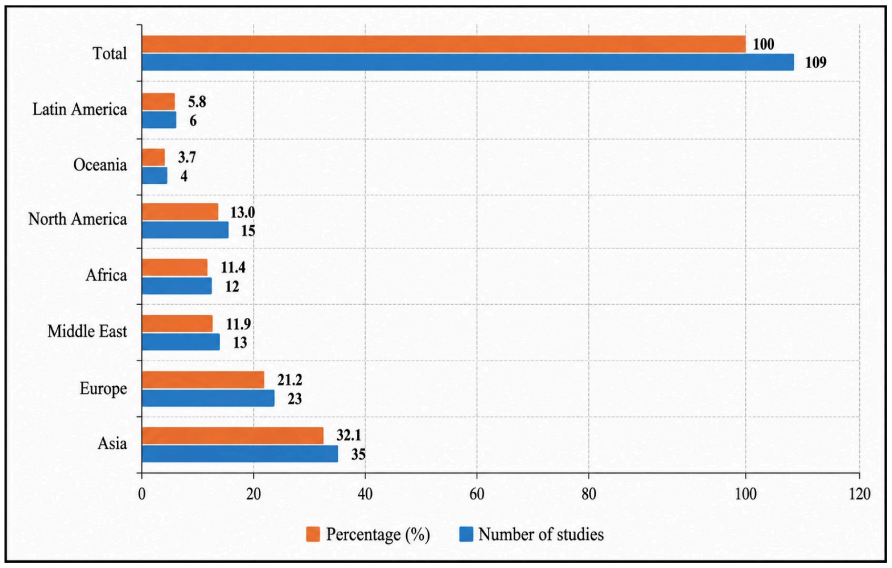


Figure 4. Geographical distribution.

The methodological approaches used in the 109 studies were coded according to the principal method used to generate or evaluate evidence (Figure 5). Simulation-based studies constitute the largest methodological group, reflecting the frequent use of computational modelling to investigate thermal, energy, daylight, airflow, and adaptive-envelope performance. Laboratory and experimental studies provide evidence concerning material behaviour and biomimetic mechanisms, while field-monitoring and case-study investigations provide comparatively more direct evidence of performance under real environmental conditions. Conceptual studies were retained where they provided a sufficiently documented architectural application or analytical framework relevant to BFD [16,50,51].

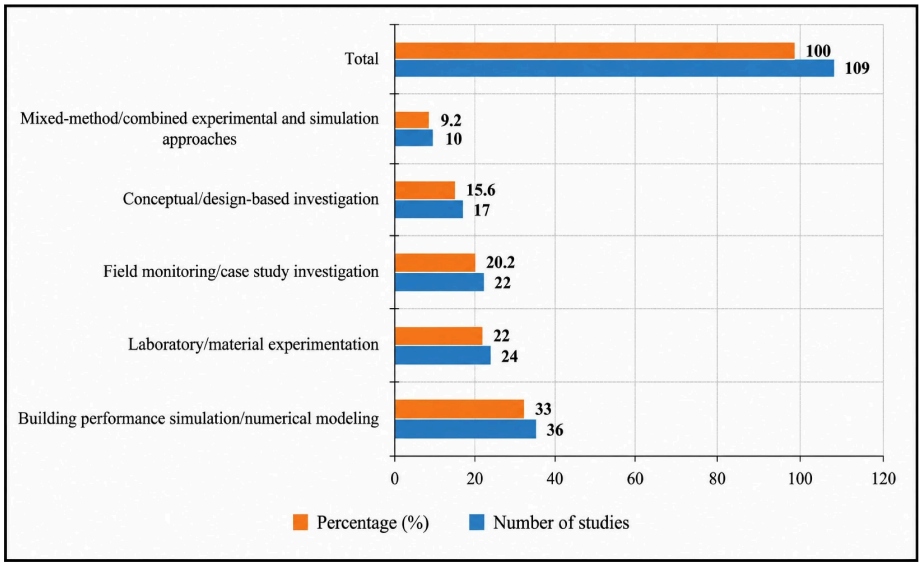


Figure 5. Research Methods.

The reviewed literature demonstrated considerable diversity in façade applications (Figure 6). Because individual studies frequently examined more than one strategy, the following categories are not mutually exclusive. The most frequently reported applications concern adaptive or responsive façades, shading, and passive thermoregulation. These strategies demonstrate a shift from biomimicry as a formal or aesthetic approach towards the functional translation of biological mechanisms into building-envelope performance. The biological analogues (Figure 7) identified in the literature were coded according to the organism or natural mechanism that informed the architectural strategy. Multiple analogues could occur within a single study. Plant-based analogues were particularly prominent because leaves, stomata, plant orientation, transpiration, and heliotropic behaviour provide mechanisms that can be translated into shading, ventilation, solar-control, and moisture-responsive façade systems. Termite mounds were frequently associated with passive ventilation and thermal regulation, while animal skins, scales, feathers, and shells provided inspiration for multilayered, protective, insulating, or responsive envelopes [17,25–27,32,47,48,52–55].

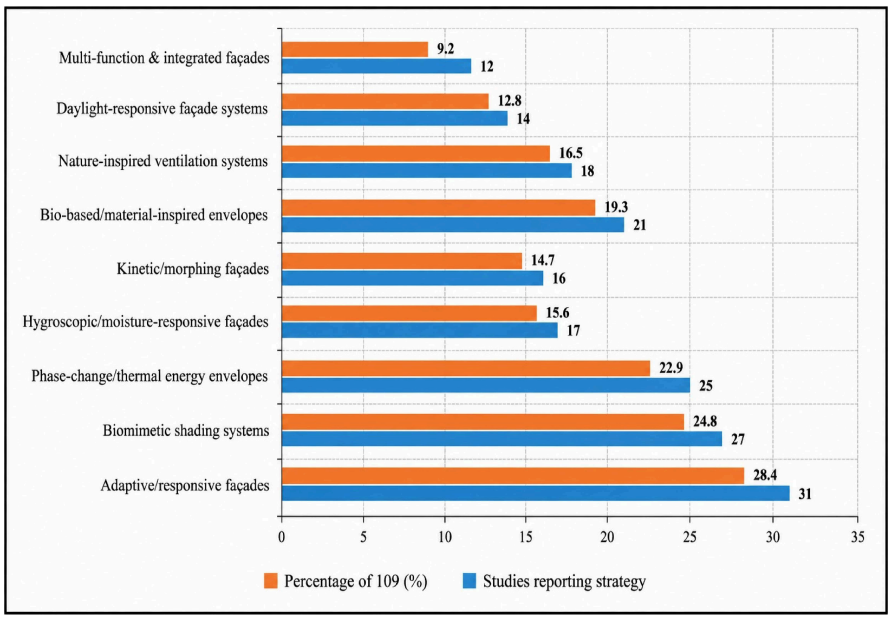


Figure 6. Façade and Envelope Strategies.

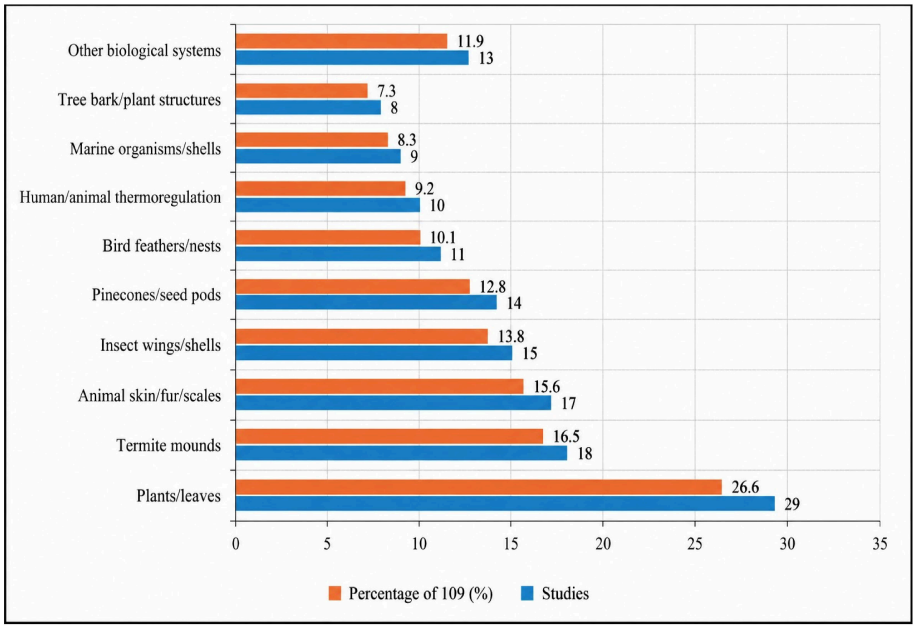


Figure 7. Biological Analogues.

The included studies covered a range of building types, although residential, office, educational, and public buildings were particularly represented (Figure 8). The predominance of residential and office applications reflects the importance of façade-mediated thermal and energy performance in buildings with substantial cooling and heating loads. Prototype and experimental structures were also important because they enabled researchers to test biomimetic mechanisms before their application to full-scale buildings.

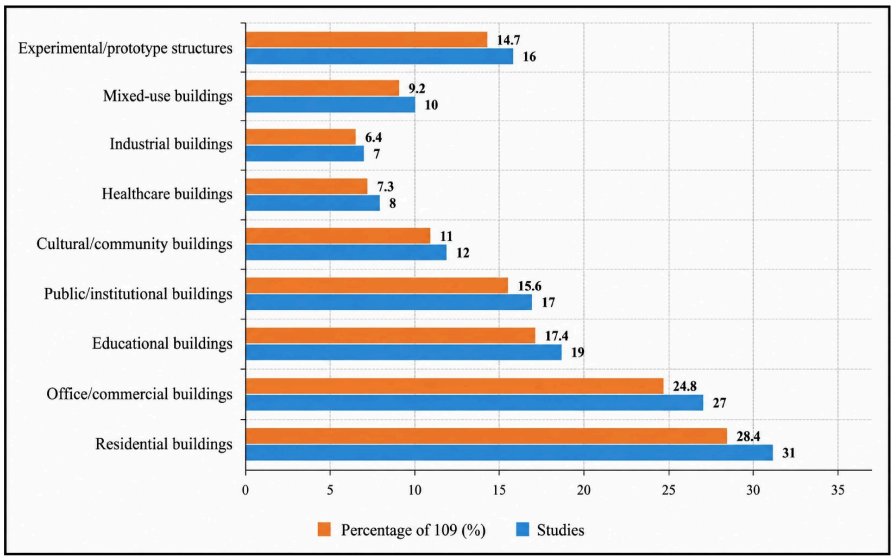


Figure 8. Building Types.

The climatic contexts were classified according to the environmental conditions relevant to façade performance (Figure 9). Since several studies investigated more than one climatic condition through simulation or comparative analysis, the categories may overlap. The evidence demonstrates that biomimetic façade strategies are investigated across substantially different environmental conditions. Hot-arid and hot-humid contexts particularly emphasise passive cooling, solar protection, ventilation, and moisture regulation, whereas temperate and cold climates place greater emphasis on heat retention, insulation, solar gain,

and adaptive control. This climatic variation is important because the performance of a biomimetic façade cannot be considered independently of local environmental conditions. The performance indicators reported across the 109 studies were also coded (Figure 10). Because individual studies frequently evaluated several outcomes, the categories overlap. Thermal performance and building energy demand were the most frequently reported performance indicators, followed by thermal comfort, solar control, and daylighting. This distribution indicates that the principal analytical emphasis of biomimetic façade research is the regulation of heat and solar exposure and the consequent implications for building energy use. However, relatively fewer studies assessed life-cycle performance, durability, maintenance, embodied carbon, or long-term operational reliability, indicating an important area for future research.

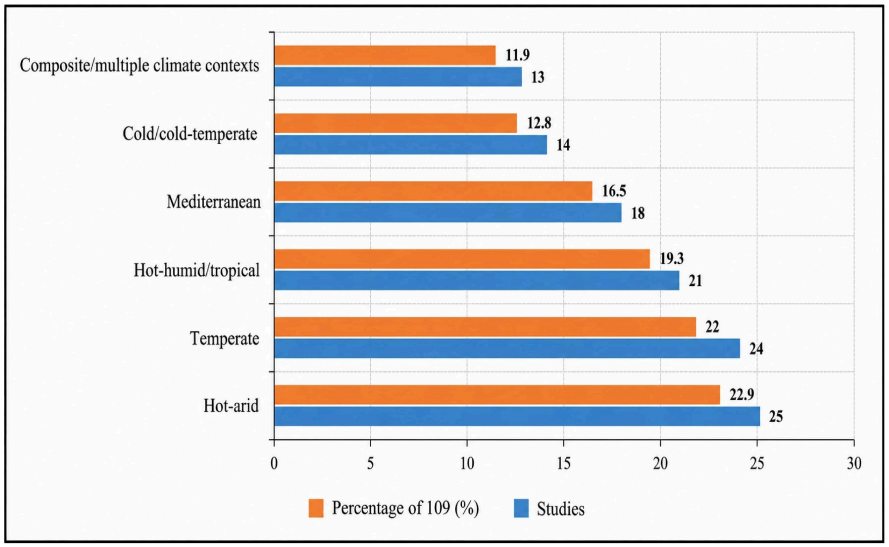


Figure 9. Climatic Contexts.

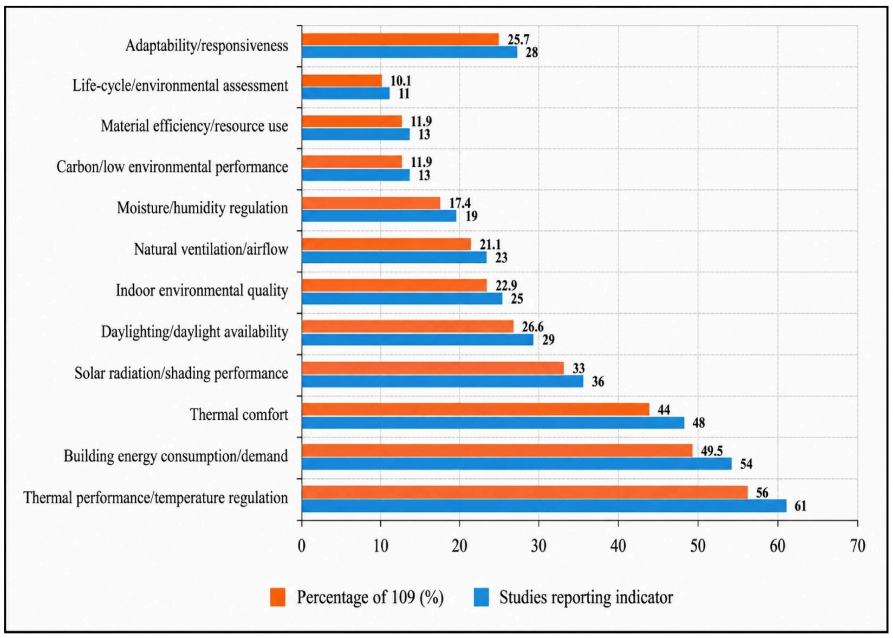


Figure 10. Performance Indicators.

The overall synthesis of the 109 included studies demonstrates a diverse and increasingly performance-oriented body of research on biomimetic architectural and building

applications. The evidence encompasses computational simulations, laboratory experiments, field monitoring, conceptual design investigations, prototype development, and integrated methodological approaches. The reviewed applications span biomimetic building forms and structures, passive environmental strategies, adaptive façades and envelopes, bio-inspired and bio-based materials, ecological systems, and responsive building technologies. Biological sources of inspiration include plants, animals, termite mounds, biological skins, natural materials, and broader ecological systems, reflecting the multidisciplinary nature of biomimetic design research.

Across the literature, energy and environmental performance constitute prominent outcome categories, particularly through strategies addressing thermal regulation, passive cooling, ventilation, solar control, and adaptive environmental response. Other reported outcomes include structural efficiency, material optimisation, embodied energy reduction, moisture regulation, daylighting, ecological integration, resource efficiency, resilience, and broader sustainability performance. The distribution of the evidence across the five dimensions further demonstrates that BA extends beyond the imitation of biological appearance to include the translation of biological processes, systems, material properties, and adaptive mechanisms into architectural and building strategies.

The descriptive analysis also reveals substantial methodological, technological, climatic, and contextual heterogeneity across the reviewed studies. Differences in building types, climatic conditions, biological models, design scales, performance indicators, and validation approaches limit the direct comparability of reported outcomes. Consequently, the evidence is more appropriately interpreted through structured thematic and descriptive synthesis than through statistical pooling of effect sizes. This approach provides a more appropriate basis for identifying recurring biomimetic strategies, understanding their performance implications, and highlighting areas requiring further empirical validation.

3.2. Study's Review Synthesis Framework: Incremental Contribution and Conceptual Boundaries of the Five-Dimensional Framework

The five-dimensional framework proposed in this study builds upon existing biomimetic classifications that distinguish biological morphology, function, process, material characteristics, behavioural mechanisms, and ecosystem relationships. Table 2 presents an analytical comparison between established classification perspectives and the proposed framework. This comparison identifies differences in organising principles rather than demonstrating the empirical superiority of the proposed framework. Instead of introducing an alternative biological taxonomy, the framework integrates established perspectives into a coherent analytical structure for interpreting architectural applications and reported building-performance outcome studies, as supported by [1,4,6,7,56–60]. Its principal contribution lies in identifying the predominant mechanism through which biological knowledge is translated into architectural design while distinguishing this mechanism from the associated functional objectives and performance outcomes.

An important conceptual distinction concerns biological function and biological process. Existing biomimetic approaches [6,57,61] commonly describe function in terms of the purpose served by a biological mechanism, whereas process refers to the operational principles through which that function is achieved. Within the proposed framework, function is therefore considered a cross-cutting performance objective rather than an independent analytical dimension. For example, an architectural strategy inspired by biological cooling mechanisms would be classified under nature as process when its principal innovation concerns heat-transfer operations, while the intended cooling effect would be recorded as a performance objective. This distinction reduces conceptual ambiguity by separating the operating mechanism from its intended architectural function.

Similarly, nature as form is distinguished from nature as material according to the principal carrier of biological inspiration. Form-oriented applications reproduce biological geometries, structural arrangements, morphological configurations, or natural patterns, whereas material-oriented applications emulate biological compositions, microstructures, fabrication processes, or functional material properties as corroborated by [4,62–65]. Consequently, a nature-inspired load-bearing geometry would primarily represent nature as form, while a bio-inspired composite whose functional performance depends on its composition or microstructure would be classified under nature as material. This distinction facilitates the interpretation of architectural applications in which biological geometry and material innovation may coexist.

The distinction between nature as process and nature as system is primarily associated with the scale, organisation, and interdependence of the biological principles being translated. Process-oriented applications reproduce identifiable mechanisms, such as heat exchange, moisture transport, ventilation, or resource transformation, whereas system-oriented applications involve relationships among multiple components, resource flows, and ecological processes [7,56,66,67]. For instance, an individual biological ventilation mechanism would be classified as nature as process, while an integrated architectural strategy coordinating ventilation, water circulation, energy exchange, and ecological interactions could be interpreted as nature as system. This distinction is particularly relevant to building-integrated ecological strategies and regenerative design approaches, where environmental performance may depend on interactions among several interconnected components [68,69].

Nature as adaptation is distinguished from the other dimensions by its emphasis on responsive behaviour under changing environmental conditions. Adaptive architectural systems may incorporate biological forms, materials, or processes; however, their primary classification under adaptation depends on whether environmental responsiveness constitutes the principal innovation [8,60,70–73]. For example, a humidity-responsive façade may be classified as nature as adaptation when the investigation focuses on changes in façade configuration or behaviour under varying humidity conditions. Conversely, research primarily examining the composition and functional properties of the moisture-responsive material would be classified under nature as material. This distinction recognises the relationship between responsive materials and adaptive building-envelope technologies without treating them as conceptually identical [60,64,72,73].

These analytical boundaries do not imply that the five biomimetic dimensions are mutually exclusive or theoretically independent. Biological morphology, processes, systems, materials, and adaptive behaviours may operate simultaneously within a single architectural application [4,7,56,58]. Nevertheless, distinguishing their predominant roles supports a more consistent thematic interpretation and facilitates comparisons among studies addressing different architectural strategies. The framework further connects biological inspiration with architectural translation mechanisms and reported performance indicators, enabling individual studies to be examined according to the biological principle adopted, the architectural component developed, and the methods used to assess its performance.

The findings are interpreted in relation to the methodological characteristics and evidential limitations of the included studies. Given the heterogeneity of research designs, building typologies, climatic contexts, biomimetic applications, and performance-assessment approaches, the synthesis relies primarily on narrative comparison, qualitative thematic analysis, and descriptive frequencies rather than statistical meta-analysis. Consequently, the identified relationships between biomimetic dimensions and sustainable building performance represent reported associations, emerging design opportunities, and context-specific technological potential rather than statistically established causal effects.

Accordingly, the proposed framework could be understood as an interpretive classification derived from the systematic synthesis of architectural research, rather than an independently validated model for predicting building performance. Its classification reliability, transferability across architectural contexts, and practical usefulness for design decision-making require further investigation. Nevertheless, the framework provides a structured basis for examining how biological knowledge is abstracted and translated into architectural strategies and how the resulting applications are evaluated in relation to sustainable building performance.

Table 2. Comparison of the study's proposed framework with the existing biomimetic classifications.

Existing Classification Perspective	Principal Emphasis (with Supporting Studies)	Distinction Introduced in this Study's Framework
Form or morphology	Biological geometry, morphological configurations, natural structural patterns, and structural optimisation inspired by organisms and natural systems [1,4,61,73].	Defines morphology as the primary architectural translation mechanism, separate from material properties and adaptive behaviour
Function	Biological functions translated into architectural performance objectives, including thermal regulation, energy efficiency, ventilation, resource optimisation, and environmental performance [4,6,9,61].	Treats function as a cross-cutting objective rather than a competing dimension
Process	Biological operating mechanisms, nature-inspired design procedures, environmental regulation, and functional processes that inform architectural and construction applications [1,4,64,67].	Separates individual functional mechanisms from coordinated systemic interactions
Ecosystem	Ecological relationships, interconnected natural systems, resource cycles, regenerative principles, and the integration of biological knowledge into sustainable built environments [1,5,61,67,74].	Incorporates ecological and multi-component interactions under nature as a system
Material	Biological material properties, natural microstructures, bio-inspired and bio-based construction materials, living materials, and associated environmental-performance considerations [2,4,5,13,64].	Identifies material properties or fabrication as the primary carrier of biological inspiration
Adaptation or behaviour	Biological responsiveness, environmentally adaptive mechanisms, climate-responsive building envelopes, and nature-inspired strategies for energy and environmental regulation [3,6,73,74].	Defines adaptation through responsive change rather than the mere presence of a biological mechanism
Proposed five-dimensional framework	Integrates biological morphology, functional processes, systemic relationships, material properties, and adaptive responses into a coherent architecture-oriented analytical structure informed by [1–65].	Connects biological inspiration, primary architectural translation, decision boundaries, and building-performance objectives.

Note: Although these publications present different classification approaches, the proposed framework integrates their perspectives into five distinct operational dimensions, with clear criteria for identifying predominant biomimetic mechanisms in architectural applications. It complements rather than replaces existing frameworks.

In architecture, such translation can occur at different biological levels, ranging from individual organisms and their morphological characteristics to behavioural mechanisms, functional processes, and interactions within broader ecosystems [4,5]. These biological levels provide a basis for understanding how knowledge from nature can be transferred into architectural design, while the specific mode of translation may involve form, process, material, system, function, or adaptive response [1,6]. Recent research further demonstrates the conceptual diversity of biomimetic architecture, encompassing applications that draw upon

biological morphology, material properties, construction strategies, functional mechanisms, behavioural processes, and ecosystem relationships [2,3]. Building on these foundations, the present study synthesises the reviewed evidence into five complementary dimensions such as nature as form, nature as process, nature as system, nature as material, and nature as adaptation to provide a structured interpretation of how biological knowledge is translated into architectural strategies and building-performance outcomes.

Building on established approaches to classifying biomimetic applications, the present study develops a five-dimensional biomimetic architectural framework comprising nature as form, nature as process, nature as system, nature as material, and nature as adaptation. The framework was derived through the thematic synthesis of the 109 studies included in the review and is intended to provide an architecture-focused analytical structure for interpreting how biological knowledge is translated into building design and performance [4,5]. The framework does not treat the five dimensions as mutually exclusive categories. Instead, they represent complementary and potentially overlapping pathways through which biological principles can inform architectural decisions, reflecting the diversity of biomimetic applications across form, function, materials, environmental processes, and adaptive systems [2,6]. A single architectural intervention may therefore incorporate multiple biological principles and modes of translation, particularly where biological processes, materials, environmental responses, and system relationships are integrated within a single design strategy [3,5].

The results in Supplementary Table S6 suggest that contemporary biomimetic architectural research extends beyond the imitation of natural appearance to encompass the translation of biological functions, behaviours, systems, materials, and adaptive mechanisms. Recent studies demonstrate, for example, the application of biological principles to adaptive solar envelopes, responsive façades, building shading systems, bio-inspired materials, and climate-responsive architectural strategies [8,9,11]. The considerable emphasis on nature as adaptation reflects growing research attention to architectural strategies capable of responding to changing environmental conditions, while the substantial representation of nature as form demonstrates the continuing importance of biological morphology, geometry, and structural organisation in architectural design [4,8]. Similarly, the presence of process- and system-oriented biomimicry indicates increasing attention to the functional mechanisms, resource flows, ecological relationships, and environmental interactions through which biological systems achieve performance and resilience [2,5,6].

Figure 11 presents a conceptual framework that illustrates how biological knowledge and natural systems translate into architectural applications through the biomimetic principles identified in the thematic analysis. The framework integrates biological inspiration with architectural translation and building-performance objectives, thereby illustrating how different biomimetic dimensions can contribute to structural, environmental, material, ecological, and adaptive outcomes [3,4]. Altogether, the findings suggest that contemporary biomimetic design has evolved toward a multidimensional approach in which biological knowledge can inform architectural form, processes, systems, materials, and adaptive responses. An architectural solution may therefore incorporate several dimensions simultaneously, such as bio-inspired morphology combined with bio-based materials, passive environmental processes, ecological system interactions, and adaptive response mechanisms. This multidimensionality is consistent with recent research demonstrating the integration of biological strategies across building envelopes, materials, environmental technologies, and broader building-life-cycle applications [5,8,10]. The five dimensions should consequently be understood as complementary analytical categories rather than mutually exclusive or hierarchical stages. Their overlap reflects the interconnected nature of biological strategies and the complexity of translating natural principles into architectural systems. Overall, the findings from the 109 reviewed studies highlight the multifaceted character of BA and

demonstrate how biological knowledge can be translated through multiple, interconnected pathways to address contemporary architectural and building-performance challenges.

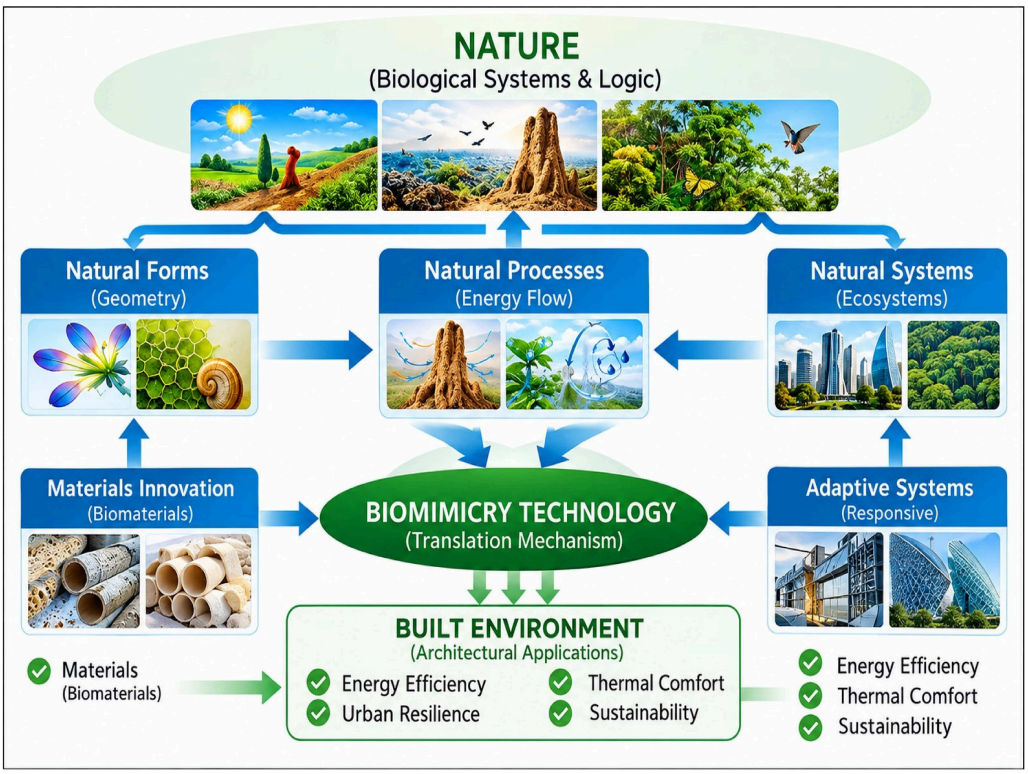


Figure 11. Conceptual framework of the biomimicry principles derived from thematic analysis. Source: Author's conceptualisation.

3.2.1. Nature as Form: Structural Efficiency and Spatial Optimisation

Nature as form was identified in 28 studies (25.7%), indicating sustained interest in biological morphology, geometry, patterns, and structural organisation within biomimetic architectural design. The reviewed literature demonstrates that form-oriented biomimicry extends beyond the visual replication of natural shapes towards the abstraction and translation of geometric and structural principles that can contribute to architectural performance [1,4]. Biological structures such as honeycombs, skeletal systems, shells, and plant geometries demonstrate relationships between form, structural organisation, loading, and material distribution that can inform architectural design and construction strategies [4,10].

The Eden Project in the United Kingdom, identified among the reviewed case studies, illustrates the application of geometrically organised biological principles to architectural structure. Its interconnected dome structures draw inspiration from cellular and honeycomb-like organisational principles, demonstrating how geometric configurations can support structural efficiency while facilitating lightweight construction and material optimisation. Similarly, the Turning Torso in Sweden represents a form-oriented biomimetic application in which the twisting configuration is associated with the structural and morphological characteristics of the human spine. The case demonstrates how biological morphology can be abstracted into a vertically organised architectural structure rather than reproduced as a literal natural form. These cases support the broader observation that biological geometry and structural organisation can provide transferable principles for architectural form generation and structural design [1,4,37]. Accordingly, the illustrative cases were used to contextualise and demonstrate the practical relevance of the identified biomimetic dimensions rather than to provide independent empirical validation of the framework.

This distinction ensures that the systematic evidence synthesis remains methodologically separate from the supplementary architectural examples and avoids double-counting or overstating the evidential contribution of individual projects.

The reviewed evidence therefore indicates that nature as form can contribute to structural efficiency, material optimisation, spatial organisation, and innovative architectural geometry. Importantly, however, its significance extends beyond morphological resemblance. Form-oriented biomimicry involves the abstraction of geometric relationships, structural configurations, and organisational principles that can influence load distribution, stability, material use, and spatial performance. The findings consequently position nature as form as a functional mode of biomimetic translation in which biological morphology provides design knowledge for developing structurally and spatially efficient architectural solutions [4,10].

3.2.2. Nature as Process: Passive Energy and Resource Optimisation

Nature as process was identified in 24 studies (22.0%), reflecting research that investigates biological processes and mechanisms such as growth, self-organisation, thermoregulation, ventilation, moisture regulation, and resource cycling as sources of architectural strategies. Unlike form-oriented biomimicry, this dimension focuses primarily on understanding how biological systems perform functions and regulate energy, materials, and environmental conditions, and subsequently translating these mechanisms into building strategies [4,6]. The reviewed studies demonstrate that process-based biomimicry is frequently associated with passive and low-energy approaches that seek to exploit naturally available environmental forces to regulate building conditions and reduce reliance on mechanically driven systems.

A prominent example identified in the reviewed literature is the Eastgate Centre in Zimbabwe, whose environmental-control strategy has been widely associated with principles observed in termite-mound thermoregulation. The case illustrates how biological principles of ventilation and thermal regulation can inform architectural strategies for managing indoor environmental conditions through airflow and thermal exchange. Rather than reproducing the physical form of a termite mound, the approach translates aspects of its environmental regulation mechanism into building-scale environmental control. This illustrates the distinction between morphological imitation and process-oriented biomimicry, in which the functional mechanism underlying a biological system becomes the principal source of architectural inspiration.

Across the reviewed studies, process-based strategies draw upon naturally available forces and environmental gradients, including wind movement, temperature differences, solar radiation, and moisture variation, to support ventilation, thermal regulation, cooling, and resource management. Such approaches can contribute to energy efficiency and indoor environmental performance by reducing the demand for active mechanical intervention, although the magnitude of these benefits depends on building type, climate, design configuration, and the method used to assess performance [3,6,30]. Recent research on biomimetic environmental technologies further demonstrates how biological mechanisms can inform thermoregulatory and climate-responsive building strategies [8,12].

The findings therefore position nature as a process as an important dimension of biomimetic architecture, particularly in relation to passive energy optimisation, environmental regulation, and resource efficiency. Its significance lies not simply in reproducing biological characteristics, but in translating the underlying mechanisms through which natural systems respond to environmental conditions and manage energy and resource flows. Such process-oriented approaches provide opportunities for climate-responsive ar-

chitectural design, while their effectiveness remains dependent on contextual and technical conditions rather than being universally transferable across building applications.

3.2.3. Nature as System: Integrated Ecological Performance

Nature as system was identified in 21 studies (19.3%), reflecting biomimetic strategies that emphasise the interconnected relationships among organisms, materials, environmental conditions, and resource flows. Rather than focusing on a single biological form or process, this dimension considers how multiple components interact within a broader system to regulate environmental conditions and support collective functioning. In architectural applications, this perspective conceptualises buildings and their surrounding environments as interconnected systems in which vegetation, water, air, energy, materials, and human activities can interact across different spatial and functional scales [2,5].

The reviewed studies indicate that system-oriented biomimicry has been applied to challenges involving microclimate regulation, biodiversity, ecological integration, urban environmental performance, and interactions between buildings and their surrounding environments. The Verticale case identified in the reviewed literature illustrates this approach through the integration of vegetation with the building and its environmental context. The interaction between plants, air movement, solar exposure, building surfaces, and surrounding environmental conditions demonstrates how vegetation can function as part of an interconnected building–environment system rather than as an isolated architectural feature. The study highlights the potential of such integrated vegetation systems to contribute to air quality, thermal regulation, urban microclimate, biodiversity, and the mitigation of environmental stresses associated with dense urban development [20,34].

The system-oriented studies further demonstrate that biomimetic design can operate across multiple levels and scales, from individual building components to building–landscape relationships and broader urban ecological systems. This perspective shifts the focus from the performance of isolated architectural features towards the interactions and relationships through which multiple elements contribute to overall environmental functioning. Recent research similarly highlights the potential for nature-inspired strategies to operate across interconnected building and environmental systems and across different stages of the building life cycle [4,5].

Accordingly, nature as a system represents an integrated approach to biomimetic architectural design in which the relationships among biological, environmental, and architectural components become central to the design process. Its contribution extends beyond individual performance improvements by encouraging consideration of ecological integration, microclimate, biodiversity, resource relationships, and environmental resilience. The findings therefore suggest that system-based biomimicry provides a broader framework for understanding buildings as components of interconnected environmental systems, although the extent of its performance benefits remains dependent on the specific ecological, climatic, and urban context in which the strategy is implemented [2,5].

3.2.4. Nature as Material: Sustainable and High-Performance Materials

Nature as material was identified in 18 studies (16.5%), representing research concerned with the material properties, hierarchical structures, compositions, and production strategies observed in biological systems and their translation into architectural applications. This dimension extends biomimicry beyond the replication of natural appearance by focusing on how biological materials achieve properties such as strength, lightness, flexibility, moisture regulation, thermal performance, and multifunctionality through their structure and composition [3,13]. Recent research also highlights the growing application

of bio-based and bio-inspired materials as part of broader efforts to reduce material impacts and support more sustainable building practices [2,5].

The reviewed studies indicate that nature as material is particularly relevant to challenges associated with resource consumption, embodied energy, material waste, and environmental impact. Bio-based materials, biodegradable materials, recycled resources, and materials inspired by biological structures have been investigated as alternatives or complements to conventional construction materials. Examples include mycelium-based materials, bio-based composites, cellulose-derived materials, and other bio-inspired material systems that seek to combine functional performance with reduced environmental burdens [3,13,14]. The development of such materials reflects increasing interest in material strategies that consider not only operational performance but also material sourcing, production, use, and end-of-life implications.

The Paper Dome identified among the reviewed case studies illustrates this principle through the use of recycled paper tubes as structural elements. The case demonstrates how an unconventional, recycled material can be translated into an architectural structural system while addressing material efficiency and resource reuse. More broadly, the reviewed literature suggests that the performance potential of biomimetic materials is often related to their structural organisation, composition, and ability to respond to environmental conditions. Biological systems provide models for achieving functional performance through efficient material organisation, rather than relying solely on greater material quantities or energy-intensive production processes [13,14]. Overall, the findings position nature as a material as an important pathway for connecting biomimetic design with material sustainability and building performance. However, the environmental and technical benefits of bio-based and bio-inspired materials remain dependent on material composition, sourcing, processing, durability, application, and life-cycle conditions. Thus, rather than assuming that biomimetic materials are inherently more sustainable than conventional alternatives, the evidence supports evaluating their performance and environmental implications within specific architectural and life-cycle contexts [3,5].

3.2.5. Nature as Adaptation: Dynamic and Responsive Systems

Nature as adaptation was the most frequently identified dimension, occurring in 32 studies (29.4%), reflecting growing research interest in architectural systems capable of responding dynamically to changing environmental conditions. The reviewed applications include adaptive shading, responsive building skins, kinetic façades, dynamic ventilation, and other environmental-control systems that modify their configuration or operation in response to external stimuli. This orientation is consistent with recent research demonstrating how biological responsiveness, particularly the adaptive behaviour of plants and other organisms, can inform the development of climate-responsive building envelopes and adaptive solar-control systems [8,11].

The principle of nature as adaptation focuses on translating the capacity of biological organisms and systems to sense and respond to environmental changes into architectural strategies. Rather than relying exclusively on fixed configurations, adaptive biomimetic systems can alter their behaviour in response to variables such as solar radiation, temperature, airflow, or other environmental conditions. The Al Bahr Towers in the United Arab Emirates, identified among the reviewed case studies, provide a prominent example through their responsive shading façade inspired by the opening and closing behaviour of plant structures in response to sunlight. The kinetic shading system changes its configuration in relation to solar exposure, demonstrating how biological principles of environmental responsiveness can be translated into building-envelope technologies [8,11].

The reviewed literature indicates that adaptive biomimetic strategies can provide opportunities for dynamic control of solar exposure, heat gain, daylight, ventilation, and indoor environmental conditions. By responding to changing environmental stimuli, such systems can potentially optimise building performance across different operating conditions rather than relying on a single static configuration [12,15]. This dynamic capability is particularly relevant to climate-responsive architecture, where environmental conditions can vary considerably over daily and seasonal cycles. However, the performance of adaptive systems depends on factors including control algorithms, response mechanisms, climatic conditions, building orientation, operational requirements, and system complexity.

The high representation of nature as adaptation in the reviewed literature therefore indicates a significant research interest in moving from static biomimetic solutions towards responsive and dynamically controlled architectural systems. Nevertheless, the findings do not imply that adaptive strategies are universally superior to static approaches. Their contribution depends on the extent to which the biological principle is appropriately translated into the architectural system and effectively responds to the environmental conditions for which it is designed. Nature as adaptation consequently represents a key dimension of contemporary biomimetic architecture, linking biological responsiveness with adaptive envelopes, environmental control, and climate-responsive building performance [8,11].

3.3. Comparative Synthesis of the Case Studies for Validation and Implications

The comparison presented in Supplementary Table S7 relates the characteristics of the selected designs to their biological principles, architectural strategies, reported performance outcomes, and corresponding building case studies. The synthesis demonstrates that biomimicry can be translated into architecture through different pathways, ranging from the abstraction of biological geometries to the emulation of natural processes, material properties, ecological relationships, and adaptive responses. These pathways correspond to the five dimensions developed in this study and illustrate the conceptual and functional diversity of biomimetic architectural design [4–6].

3.3.1. Nature as Form: Eden Project and Turning Torso

The Eden Project and Turning Torso illustrate form-oriented biomimicry through the use of geometry, structural organisation, and morphological abstraction. The Eden Project employs interconnected geodesic dome structures whose geometric configuration supports structural stability, efficient load distribution, and relatively lightweight construction. Its cellular and honeycomb-like organisation provides an architectural example of how patterns observed in nature can inform structural geometry and material optimisation. Similarly, Turning Torso translates the twisting configuration of a human torso into a vertically organised architectural form. The building's rotating composition demonstrates how biological morphology can be abstracted into architectural geometry to generate distinctive spatial and structural characteristics. These examples indicate that nature as form extends beyond visual resemblance and may involve the translation of geometric and organisational principles into architectural structures [1,4,10].

The comparison also demonstrates that form-oriented biomimicry can contribute to structural and spatial innovation by connecting architectural geometry with loading conditions, material distribution, stability, and spatial organisation. However, the performance contribution of a biomimetic form depends on its structural design, construction technology, material selection, and environmental context. Accordingly, the cases should be interpreted as examples of how biological morphology can inform architectural decision-making rather than as evidence that all biomorphic geometries automatically reduce material consumption or improve structural performance.

3.3.2. Nature as Process: Eastgate Centre and Bullitt Centre

The Eastgate Centre and Bullitt Centre illustrate process-oriented biomimicry through the translation of natural environmental and resource-management principles into building strategies. The Eastgate Centre is commonly associated with the thermoregulatory and ventilation principles observed in termite mounds. Its environmental-control approach demonstrates how biological mechanisms related to airflow, thermal exchange, and internal environmental regulation can inform passive or low-energy building strategies. In contrast, the Bullitt Centre represents an integrated approach to resource management, incorporating strategies related to energy generation, water management, and resource cycling. Its relevance to nature as process lies in the attempt to manage building resources through interconnected flows rather than treating energy and water systems as isolated technical components.

The comparison between these cases indicates that process-based biomimicry can address different aspects of building performance, including thermal regulation, ventilation, energy use, water management, and resource efficiency. Whereas the Eastgate Centre focuses more directly on environmental regulation through airflow and thermal processes, the Bullitt Centre demonstrates the application of resource-cycle principles within building operation. Such approaches are consistent with research emphasising the potential of biomimicry to translate biological mechanisms into passive environmental strategies and low-carbon building systems [3,6,15]. Nevertheless, the outcomes of process-oriented strategies depend on climatic conditions, building configuration, operational requirements, and the extent to which the biological process is appropriately adapted to the architectural context.

3.3.3. Nature as System: Bosco Verticale and Gardens by the Bay

Bosco Verticale and Gardens by the Bay illustrate system-oriented biomimicry through the integration of biological, architectural, and environmental components. Bosco Verticale incorporates substantial vegetation into high-rise residential buildings, creating an interconnected relationship among plants, building surfaces, air movement, solar exposure, and the surrounding urban environment. The case demonstrates how vegetation can function as part of a building–environment system, with potential implications for microclimate regulation, shading, air quality, biodiversity, and habitat provision [75]. Gardens by the Bay similarly demonstrates an integrated approach involving vegetation, ecological processes, water management, irrigation, and environmental control. Its design combines architectural structures with landscape and ecological systems to support a broader environmental and public-space function.

The comparison suggests that nature as a system differs from strategies focused on individual forms, processes, or materials because it emphasises interactions and synergies among multiple elements. System-oriented biomimicry therefore considers buildings as components of wider ecological and environmental networks rather than as isolated objects. This interpretation is consistent with recent research that highlights the role of interconnected biological and environmental systems in sustainable building design, ecological integration, and life-cycle performance [2,5]. However, the term self-sustaining should be used cautiously, since the actual performance of integrated green systems depends on irrigation, maintenance, climate, plant selection, technical infrastructure, and long-term management.

3.3.4. Nature as Material: Paper Dome and Mycelium-Based Insulation

The Paper Dome and mycelium-based insulation illustrate material-oriented biomimicry through the use of alternative materials and the translation of biological or resource-efficient material principles into architectural applications. The Paper Dome uses recycled paper

tubes assembled into a structural configuration, demonstrating how a lightweight and unconventional material can be adapted for architectural construction. Its relevance to nature as a material is associated with material efficiency, resource reuse, and the exploration of alternatives to conventional structural materials. Mycelium-based insulation, by comparison, uses fungal growth and agricultural waste to produce a bio-based material with potential applications in thermal insulation and low-impact construction.

Together, these cases demonstrate that material-oriented biomimicry may involve either the use of bio-based materials or the development of architectural systems inspired by the properties, organisation, and production strategies of biological materials. Relevant properties include low density, thermal insulation, biodegradability, resource efficiency, and the potential for lower environmental impacts, although these characteristics vary according to material composition, processing, durability, and application [3,13,14]. The comparison therefore indicates that nature as material can support material innovation and sustainability, but its benefits should be evaluated through technical testing and life-cycle assessment rather than assumed solely from biological origin.

3.3.5. Nature as Adaptation: Al Bahr Towers and One Ocean Pavilion

The Al Bahr Towers and One Ocean Pavilion illustrate adaptation-oriented biomimicry through responsive building-envelope and environmental-control strategies. Al Bahr Towers incorporates a dynamic shading system inspired by the responsive behaviour of plant structures. The shading elements adjust their configuration in relation to solar exposure, providing a mechanism for controlling solar radiation and potentially reducing heat gain and cooling demand. This case demonstrates how biological responsiveness can be translated into kinetic façade systems and sensor-supported environmental control [8,11].

The One Ocean Pavilion provides a further example of adaptation-oriented design through building elements inspired by biological gill structures. Its façade and ventilation-related features demonstrate how biological principles of exchange and environmental interaction can inform the design of responsive or climate-oriented architectural systems. The comparison between the two cases shows that nature as adaptation may involve different types of environmental response, including solar control, airflow management, ventilation, and dynamic modification of building components. Such strategies are increasingly examined in research on adaptive façades, responsive envelopes, and climate-responsive architectural technologies [9,12,15].

Overall, the comparison indicates that adaptive biomimetic systems can provide opportunities for adjusting building performance in response to changing environmental conditions. However, their effectiveness depends on the responsiveness of the mechanism, control strategy, maintenance requirements, climatic context, and operational performance. Adaptive systems should therefore not be assumed to be universally superior to static solutions; rather, their value lies in the possibility of matching building behaviour more closely with changing environmental demands.

3.3.6. Overall Comparative Implications

The case-study synthesis demonstrates that the five biomimetic dimensions address different but interconnected architectural concerns. Nature as form primarily relates to geometry, structural organisation, and spatial optimisation; nature as process concerns environmental mechanisms and energy or resource flows; nature as system emphasises interactions among buildings, organisms, and ecological conditions; nature as material focuses on material properties, production strategies, and life-cycle implications; and nature as adaptation addresses dynamic responses to changing environmental conditions. These

distinctions provide an analytical structure for comparing diverse biomimetic applications while recognising that a single project may operate across more than one dimension.

The cases further indicate that biomimetic design should not be interpreted as a single method or uniformly effective intervention. Instead, its contribution depends on the biological principle selected, the level of abstraction, the architectural translation, the performance objective, and the context in which the strategy is implemented. The comparative assessment therefore supports the framework proposed in this study by demonstrating how biological knowledge can be translated into structural, environmental, material, ecological, and adaptive building strategies. It also highlights the need for further empirical validation through monitored performance, experimental testing, life-cycle assessment, and context-sensitive comparison across building types and climatic conditions [3,5,8].

3.4. Advancements in Building Biomimetic Strategies, Technology and Sustainability

Biomimetic materials, inspired by the principles and efficiencies found in nature, are revolutionising industries, including architecture and construction. These materials, which replicate the natural world's inherent solutions, offer sustainable alternatives that reduce environmental impact and improve performance. Figure 12 below represents the general distribution pattern of six identified main biomimetic material and technology themes found across the 109 reviewed papers. The self-healing concrete accounts for the biggest share of the analysed category and equals 27 articles or 24.77%. The responsive façades take second place with 20 papers or 18.35%, which underlines the special interest in the scientific community in such biomimetic materials. The biodegradable plastic, biodegradable composites, and similar materials constitute another 17.43% or 19 papers, which confirms the tendency for researchers to focus on biodegradable materials. Further, the superhydrophobic surfaces account for 16 papers or 14.68%. Materials with structural biomimetic properties inspired by bones and trees comprise another 15 papers or 13.76%. Finally, the photovoltaic materials inspired by leaves were found in 12 papers or 11.01%. All six materials account for 109 papers or 100%.

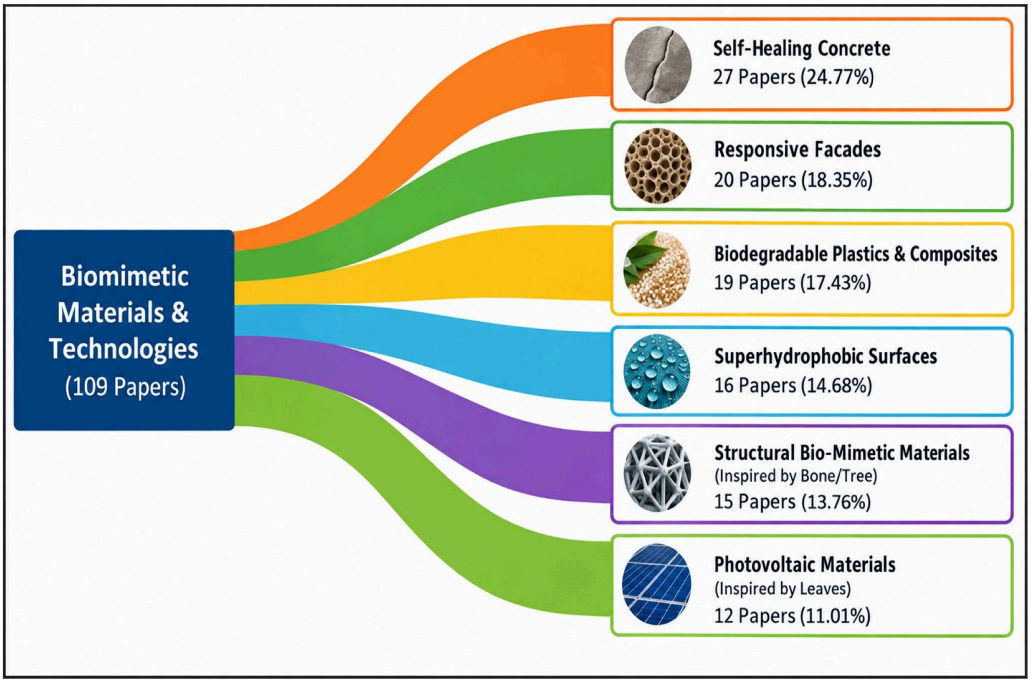


Figure 12. Summary of reviews for Advancements in Biomimetic Materials and Technologies. Source: Author's Conceptualisation.

These advancements in biomimetic materials are transforming how buildings interact with their environment, promoting energy efficiency, sustainability, and resilience. By learning from nature, architects and engineers are creating buildings that are not only functional and efficient but also harmonious with the natural world. In accordance with the present results, previous studies, such as [2,4,6], have demonstrated that biomimetic technology draws inspiration from nature's time-tested strategies to design sustainable solutions for urban environments. By studying the principles and processes of natural systems, architects, planners, and engineers can create cities that are more efficient, resilient, and harmonious with the environment. By fostering a symbiotic relationship between nature and urban environments, biomimicry can address pressing challenges like climate change, resource scarcity, and urban sprawl. As cities grow, embracing nature's designs can ensure they evolve into resilient, regenerative systems that benefit both humans and the planet [73,74].

Biomimicry or learning from nature to create technical solutions, is a potential approach to contribute to more sustainable development and energy efficiency. To achieve sustainable architectural performance, buildings must interact with the environment and adapt to climatic conditions. Given this, adaptive façades using biomimetic approaches have been proposed as solutions for enhancing buildings' energy efficiency, as shown by [37], which is essential for sustainable design. In recent years, many studies have investigated the performance of buildings in which biomimetic adaptive facades have been applied. Many of the results reveal that the application of biomimetic adaptive facades can enhance buildings' energy efficiency. The outcomes of this investigation support the conclusions of a large body of earlier research in this area. For instance, previous research on morphological manipulations of building facades to influence thermal performance has been explored by [39]. The study's findings emphasise that changes in surface geometry can create microclimates, acting as effective thermal barriers. Additionally, using the skin structure of elephants as inspiration for designing textured façade panels offers a promising approach, providing efficient evaporative cooling. The impact of surface area-to-volume ratios differs among various surface roughness profiles, highlighting the potential of this method. By applying an evolutionary-based design approach, the research shows how incorporating characteristics of elephant skin into architectural design can improve cooling performance and enhance thermal regulation.

3.5. The Transforming Role of Adaptive Facades in Biomimicry

Adaptive strategies are increasingly prominent in the reviewed evidence. The façade of a building plays a pivotal role in determining the building's performance. It serves as a buffer that not only defines the architectural appearance of the structure but also separates and protects the indoor environment from external climatic conditions. Figure 13 illustrates the transformative role of adaptive façades in biomimicry-driven architecture by highlighting the major thematic areas and their relative contributions within the reviewed studies. The findings reveal that Exterior Green Façades of Buildings constitute the most dominant theme, accounting for 35.78% of the studies, emphasising the integration of vegetation systems for thermal regulation, biodiversity enhancement, and environmental sustainability. This is followed by Innovative Dynamic Adaptive Façades (25.69%), which focus on technologically responsive building envelopes that adjust to environmental conditions in real time. Sustainable Adaptive Façades featuring dynamic shading systems represent 20.18%, while Smart Materials in Adaptive Façades account for 18.35%, highlighting the growing importance of intelligent, climate-responsive materials in achieving energy-efficient and sustainable architectural design.

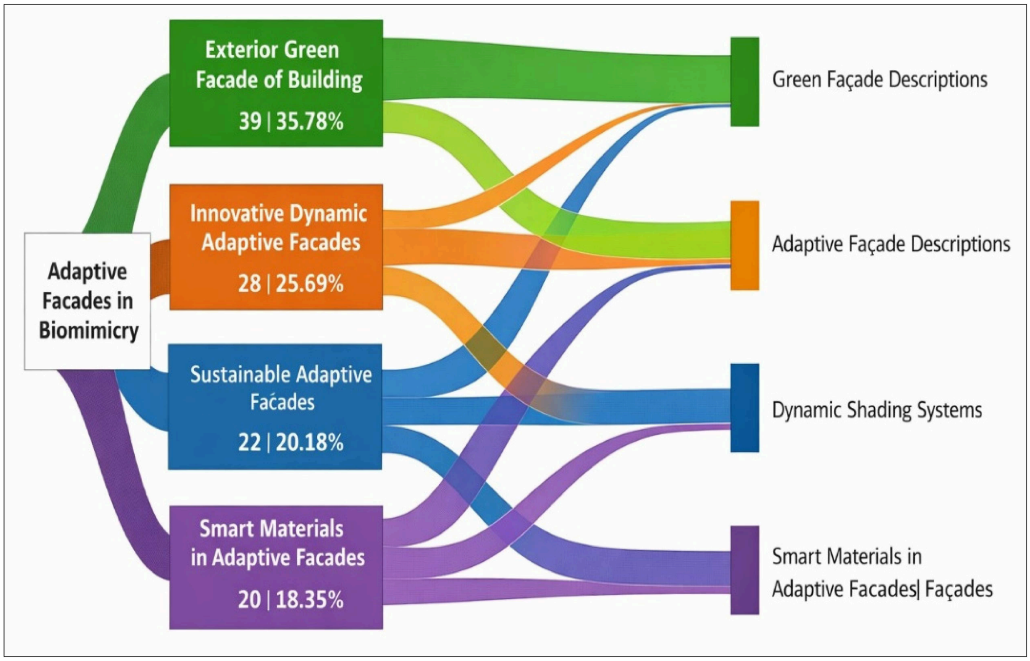


Figure 13. The review summary of the Transforming Role of Adaptive Facades in Biomimicry.

The findings of the present study are consistent with previous investigations [41,44,71], which describe adaptive façades as building-envelope systems incorporating active, dynamic, interactive, kinetic, or responsive mechanisms to regulate their performance under changing environmental conditions. These systems represent an important development in climate-responsive architecture because they can modify their physical configurations, material properties, or operational behaviours in response to variations in solar radiation, temperature, daylight availability, and other environmental parameters. Integrating adaptive technologies into building envelopes therefore creates opportunities to improve environmental regulation, indoor thermal and visual comfort, and overall building performance [42,45,71]. Furthermore, increasing concerns regarding global energy consumption and building-related environmental impacts have reinforced the importance of façade design in sustainable architecture. As the primary interface between indoor and outdoor environments, the building envelope plays a critical role in regulating solar heat gain, daylight penetration, and thermal exchange. Consequently, appropriately designed adaptive façade systems can contribute to reducing heating, cooling, and lighting demands, although the magnitude of these benefits depends on climatic conditions, control strategies, building characteristics, and operational performance [39,42,43,45].

While discussing the importance of adaptive facades, a building envelope that can adapt to environmental variations offers transformative potential for energy efficiency. By responding to changes in temperature, solar radiation, and other climatic factors, such adaptive systems can minimise energy consumption while maintaining optimal indoor thermal and visual comfort. For example, a façade designed with automated shading systems can adjust based on the intensity of sunlight, thereby reducing reliance on artificial cooling.

3.6. Exterior Green Facade of Building

This finding suggests that adaptive facades consist of green facades that incorporate vegetation, such as vertical gardens or green walls, to improve insulation, enhance air quality, and reduce heat gain. Green façades involve the strategic cultivation of climbing plants or vegetative systems along the exterior façade of a building. This architectural approach creates a natural sunscreen that helps mitigate solar gain by shading the building's surface

and reducing heat absorption. By limiting direct sunlight exposure, green façades contribute to lower indoor temperatures, encouraging energy conservation and reducing the need for energy-intensive cooling technologies. This type of façade typically uses climbing plants that grow directly on the building's walls or a supporting structure, such as trellises, cables, or mesh systems. Over time, the plants create a living layer of greenery that not only improves thermal insulation but also enhances air quality by filtering pollutants and producing oxygen.

In addition to environmental benefits, green façades offer aesthetic and psychological advantages. The integration of greenery into urban structures enhances visual appeal, contributes to urban biodiversity by providing habitats for birds and insects, and promotes a sense of well-being for building occupants and passersby. For instance, Verticale, in Milan, Italy (Supplementary Figure S1a–d), adopted green feature facades that provide both thermal regulation and aesthetic appeal as follows: (a) showing the external view demonstrating the integration of vertical greenery within high-rise residential architecture; (b) showing the detailed façade view showing balcony-based vegetation systems that provide shading, biodiversity, and microclimatic regulation; (c) depicting the environmental performance diagram illustrating the ecological functions of the vertical forest system, including CO_2 absorption, oxygen production, air filtration, humidity control, and acoustic insulation; (d) Sectional and seasonal analysis of the building showing the relationship between vegetation, occupants, daylight penetration, and climatic adaptation across different seasons.

Bosco Verticale (Vertical Forest) reinterprets conventional urban building envelopes through the integration of living vegetation into its architectural façades. Rather than relying exclusively on conventional construction materials and mechanical environmental-control technologies, the project incorporates trees, shrubs, and other plant species to create a dynamic architectural composition that changes in appearance across seasons. As discussed by [75], this approach integrates vegetation as a biological shading and environmental-regulation component, contributing to the interaction between architecture and urban ecology. The vegetated façade has the potential to moderate solar exposure, provide shading, support local microclimatic regulation, and enhance urban biodiversity. These characteristics demonstrate how building-integrated vegetation can complement conventional architectural technologies and contribute to environmentally responsive and sustainable urban design.

One of the primary benefits of the Vertical Forest is its ability to enhance urban biodiversity. The diverse plant species create a vertical ecosystem that integrates with the existing urban environment while providing habitats for wildlife. Early estimates suggested that the towers could support approximately 1600 bird and butterfly species, encouraging the city's repopulation of flora and fauna. In doing so, the Vertical Forest fosters a harmonious relationship between architecture and nature, contributing to a greener and more biodiverse urban landscape. Other examples of green façades include the CaixaForum Museum in Madrid, Spain, and the One Central Park complex in Sydney, Australia, which demonstrate how this innovative design approach can merge functionality with environmental sustainability.

3.7. The Innovative Dynamic Adaptive Facades

The results of this study indicate that adaptive façades share a similar goal with green façades in enhancing building performance, energy efficiency, comfort, and visual appeal. However, instead of relying on natural vegetation, adaptive façades employ artificial materials integrated with advanced technologies to respond dynamically to environmental changes. Adaptive façades significantly improve building performance by responding to

environmental changes in real time. These façades help manage daylight effectively, which decreases the need for artificial lighting and reduces overall energy use. By combining passive strategies like natural ventilation with active technologies such as automated shading, adaptive façades play a vital role in promoting sustainability and ensuring occupant comfort. Their capability to adjust to various climatic conditions, including daily and seasonal shifts, makes them crucial for contemporary energy-efficient buildings.

The adaptive facades use innovative systems such as motorised panels, responsive glass, or smart shading devices that can adjust their position, opacity, or thermal properties based on factors like sunlight intensity, temperature, and wind conditions. By doing so, adaptive façades optimise indoor thermal comfort and reduce energy use for lighting, heating, and cooling while enhancing the building's overall sustainability. For instance, the Al Bahar Towers in Abu Dhabi (Supplementary Figure S2a–d) feature an innovative application of biomimetic adaptive architecture through a computer-controlled kinetic façade incorporating operable shading elements that respond to changing solar conditions throughout the day [45,72]. Inspired by the traditional Islamic mashrabiya, the façade consists of geometrically configured shading modules that open and close in response to solar exposure, helping regulate daylight penetration, solar heat gain, and visual comfort. It illustrates the architectural and technological characteristics of this responsive façade system: (a) presents an exterior view of Al Bahar Towers, highlighting the integration of the kinetic shading system into the building envelope; (b) illustrates the triangular, mashrabiya-inspired shading modules designed to respond to solar radiation; (c) depicts the digital parametric modelling and geometric transformation processes employed in developing the adaptive façade units; and (d) presents an exploded axonometric representation of the façade assembly, showing the relationship between the structural framework, shading modules, and external building skin. Collectively, these features demonstrate how kinetic shading systems can reduce excessive solar exposure and glare while maintaining useful daylight penetration, thereby potentially reducing cooling and artificial lighting requirements [45,72]. The Al Bahar Towers façade represents a notable example of integrating computational design, responsive technologies, and culturally inspired architectural geometry to improve environmental performance and support sustainable building design.

This innovative design not only enhances energy efficiency but also connects the building to its cultural heritage through the reinterpretation of the traditional Mashrabiya shading system. The towers feature a dynamic mashrabiya system developed by Aedas' computational design team. The group used parametric modelling to model how the actuated façade panels would react to different angles of incident sunlight and solar exposure throughout the entire year. The façade operates as an independent curtain wall, positioned two meters from the building's exterior. Each triangular panel, coated with fibreglass, is programmed to adjust according to the sun's movement, reducing solar gain and glare. During the evening and night, the screens close entirely, revealing more of the façade and providing a unique nighttime aesthetic.

These findings are consistent with previous studies [42,45,72], which highlight the potential of dynamic and kinetic shading systems to reduce excessive solar heat gain, improve daylight regulation, and enhance the environmental performance of building envelopes. In the case of Al Bahar Towers, the mashrabiya-inspired kinetic façade incorporates computer-controlled shading modules that respond to changing solar conditions, thereby limiting direct solar radiation and potentially reducing cooling energy requirements [45]. Furthermore, the responsive shading system filters incoming sunlight while maintaining opportunities for useful daylight penetration and external views, which may reduce dependence on artificial lighting under appropriate operating conditions [42,45]. By integrating traditional Islamic architectural principles with contemporary computational design and

automated façade technologies, Al Bahar Towers demonstrate how culturally responsive architectural solutions can contribute to thermal comfort, energy efficiency, and sustainable building design [45,72].

To achieve sustainable design, incorporating adaptive façade systems into building designs is no longer optional but necessary for achieving sustainability goals. By addressing both energy efficiency and occupant comfort, these innovations bridge the gap between environmental demands and functional performance. Moving forward, the integration of such systems will likely define the future of sustainable architecture, enabling buildings to adapt seamlessly to their surroundings while minimising their environmental footprint.

3.8. Dynamic Adaptive Façade Shading Systems, Building Performance, and Practical Implementation Challenges

Enhancing building performance through dynamic shading systems represents an important advancement in adaptive façade design, particularly in responding to changing climatic conditions, solar radiation, and seasonal environmental variations [39,42,45,49]. Unlike conventional static shading devices, dynamic façade systems incorporate adjustable, kinetic, or environmentally responsive components that regulate solar exposure, daylight penetration, and heat transfer according to prevailing environmental conditions. These systems can improve daylight distribution while limiting excessive solar heat gain, glare, and visual discomfort, thereby supporting indoor environmental quality and potentially reducing building energy demand [42,70,71,76–79]. During summer, adaptive shading elements can restrict direct solar radiation and associated cooling loads, whereas controlled solar admission during winter may support passive heating and daylight utilisation. Nevertheless, their effectiveness depends on climatic conditions, façade orientation, control strategies, building configuration, and operational requirements [42,49,71,76,80].

Despite these potential performance advantages, the practical implementation of dynamic façade technologies presents significant technical, economic, and operational challenges. A major consideration is the initial capital investment associated with specialised façade components, automated control systems, environmental sensors, actuators, and installation requirements. Compared with conventional static shading solutions, dynamic façade technologies may involve additional expenditure for system integration, commissioning, maintenance, component replacement, and performance monitoring. The complexity of responsive façade configurations and their associated operational requirements is discussed in previous investigations [45,79]. Consequently, their economic feasibility should be assessed against anticipated operational energy savings, building typology, climatic conditions, maintenance requirements, and expected service life. Comprehensive life-cycle cost assessment is therefore recommended to establish whether the projected energy and comfort benefits justify the additional investment.

Another important challenge concerns the mechanical complexity and long-term operational reliability of kinetic façade systems. Movable shading components may be exposed to environmental stressors, including wind loads, temperature fluctuations, moisture, dust accumulation, and repeated mechanical movement. These conditions introduce potential risks of actuator deterioration, mechanical fatigue, sensor malfunction, and reduced operational reliability. Existing studies of kinetic and adaptive façade design highlight the importance of understanding movement mechanisms, responsive configurations, and system integration [45,79]. However, these studies do not, by themselves, establish the frequency or magnitude of long-term component failures. Accordingly, the design and implementation of adaptive façades should incorporate appropriate consideration of mechanical durability, environmental exposure, maintenance accessibility, control-system robustness, and compo-

nent replacement strategies to support sustained performance throughout the building's operational life.

Furthermore, integrating multiple mechanical, electronic, and automated control components into adaptive façade systems can increase maintenance complexity and create a need for specialised technical expertise. Inadequate maintenance, sensor malfunction, actuator deterioration, or improper control-system calibration may compromise shading effectiveness, increase operational expenditure, and adversely affect indoor thermal and visual comfort [42,63,76]. The interaction between mechanical components, environmental sensors, and automated control mechanisms therefore requires careful consideration throughout the design, installation, commissioning, and operational stages. These considerations highlight the importance of robust mechanical configurations, accessible maintenance arrangements, reliable control strategies, periodic performance evaluation, and appropriate manual override mechanisms to ensure sustained functionality and occupant satisfaction [76,79].

The durability and environmental performance of bio-based and biologically inspired façade materials also require critical consideration. Although biomimetic and smart materials offer opportunities for resource efficiency, environmental responsiveness, and improved building-envelope performance, their long-term effectiveness depends on material composition, fabrication techniques, climatic exposure, operational conditions, and maintenance practices [44,63–65,81]. In particular, moisture-responsive, thermochromic, electrochromic, and other biologically inspired material systems may experience changes in functional behaviour following repeated exposure to humidity, ultraviolet radiation, thermal cycling, and mechanical stress. Such exposure can potentially contribute to material deterioration, dimensional instability, reduced responsiveness, and declining functional performance, although the extent of degradation varies across material types and applications [63–65,81]. Consequently, laboratory-scale performance assessments should be complemented by accelerated ageing tests, material durability investigations, environmental exposure assessments, and long-term operational monitoring before definitive conclusions regarding service life, environmental benefits, and practical reliability are established. These evaluations are essential for supporting the responsible integration of innovative biomimetic materials into sustainable and climate-responsive building envelopes.

The successful implementation of adaptive façade systems depends on the effective integration of intelligent control technologies, responsive building-envelope components, and building-management infrastructure. Previous studies have emphasised the importance of computational design, environmental responsiveness, and advanced material technologies in optimising adaptive façade performance [42,63,76,79,81]. Nevertheless, operational challenges associated with sensor accuracy, system interoperability, control calibration, communication reliability, and maintenance requirements may affect the effectiveness and consistency of automated façade responses. Furthermore, automated control strategies may not always align with occupants' thermal and visual comfort preferences, particularly under rapidly changing environmental conditions or where individual comfort requirements differ. Consequently, adaptive façade systems should incorporate flexible control mechanisms, reliable environmental monitoring, appropriate occupant interaction, and accessible maintenance arrangements. An integrated, user-centred approach is therefore essential for balancing automated environmental regulation, energy efficiency, operational reliability, and indoor environmental comfort. Such an approach can strengthen the practical applicability and long-term sustainability of intelligent adaptive building envelopes [42,45,79].

From a sustainability perspective, the environmental advantages of adaptive façade systems should be assessed across their entire life cycle rather than exclusively through operational energy performance. The production, transportation, installation, maintenance,

replacement, and disposal of specialised components may generate environmental burdens that offset some operational benefits [80–82]. Therefore, evaluations should consider embodied environmental impacts, material durability, maintenance frequency, component replacement, and end-of-life management alongside potential reductions in heating, cooling, and lighting demand. Such assessments are particularly important when comparing conventional shading technologies with mechanically complex or material-intensive adaptive alternatives.

Overall, dynamic shading systems and other adaptive façade innovations offer promising opportunities for improving thermal comfort, daylight regulation, energy efficiency, and environmental responsiveness [70–72,76]. However, their practical effectiveness depends on technical reliability, economic feasibility, climatic suitability, maintenance requirements, material durability, and the quality of operational control. The reviewed evidence therefore supports cautious interpretation of reported performance benefits, particularly where findings are derived primarily from simulations, conceptual investigations, or limited experimental validation. Further research involving full-scale prototypes, long-term field monitoring, comparative life-cycle assessment, and post-occupancy evaluation would strengthen understanding of the operational performance and practical scalability of biomimetic adaptive façade systems. Table 3 summarises six prominent categories of adaptive façade innovations, with accompanying architectural illustrations, highlighting both their potential sustainability contributions and practical application contexts.

3.9. Smart Materials in Adaptive Facades

Adaptive façades incorporating smart materials represent an important advancement in contemporary architectural design, enabling building envelopes to respond dynamically to changing environmental conditions. These innovations offer opportunities to improve energy efficiency, thermal comfort, daylight regulation, and overall building sustainability through the integration of biologically inspired mechanisms, environmentally responsive materials, and intelligent control technologies [8,23,83–85]. Three principal categories of smart-material applications are identified in this review: (i) thermoregulating skins, (ii) bio-inspired and hygroscopic materials, and (iii) dynamic shading systems. Although these technologies demonstrate considerable potential for improving building performance, their practical implementation requires careful consideration of initial capital investment, material durability, maintenance complexity, operational reliability, and lifecycle environmental impacts [5,23,85]. Thermoregulating skins constitute an innovative category of responsive building envelopes that emulate the adaptive thermal-regulation mechanisms of biological organisms. Inspired by the protective and environmental functions of natural skins, these systems seek to regulate heat transfer, solar radiation, and indoor thermal conditions through the application of thermally responsive materials, smart glazing technologies, and adaptive envelope configurations [85–88].

Their capacity to respond to external temperature fluctuations can potentially reduce unwanted heat gains and losses, improve indoor thermal stability, and minimise dependence on mechanical heating and cooling systems. Furthermore, the integration of responsive materials with computational design and environmental optimisation strategies provides opportunities to improve building-envelope performance across different climatic conditions [9,50]. Nevertheless, the practical deployment of thermoregulating skins is constrained by material costs, fabrication complexity, installation requirements, and uncertainties surrounding long-term performance. Repeated exposure to temperature variations, ultraviolet radiation, moisture, and other environmental stressors may affect material responsiveness and operational efficiency. Consequently, the selection of thermoregulating materials should consider not only their initial thermal properties but also their durability,

maintenance requirements, replacement frequency, and compatibility with conventional construction systems [18,23].

Bio-inspired and hygroscopic materials represent another important development in adaptive façade technologies. These bio-inspired materials and systems emulate the structural configurations, environmentally responsive behaviours, and functional characteristics observed in biological organisms, particularly plants and animals, to enhance environmental adaptability, material efficiency, and the sustainability of building-envelope applications [26,83,86–88]. Hygroscopic materials, in particular, respond to variations in ambient humidity through moisture absorption and desorption, which may produce reversible dimensional changes and enable passive façade movement without continuous external energy input. Research on bio-inspired adaptive façades and environmentally responsive materials highlights the potential of moisture-responsive systems to support passive environmental regulation and climate-responsive architectural applications. In particular, hygromorphic building-envelope concepts offer opportunities to translate biological moisture-response mechanisms into adaptive architectural components that may reduce dependence on mechanically operated control systems [83,84,86]. Similarly, nature-inspired material innovations offer opportunities to improve structural efficiency, optimise material utilisation, and reduce dependence on conventional resource-intensive construction products. By translating biological structures, material properties, and functional mechanisms into engineering and architectural applications, biomimetic approaches can support the development of lightweight, resource-efficient, and potentially lower-impact construction materials [48,55,63].

However, the long-term durability of bio-inspired and hygroscopic materials remains a significant challenge to their widespread architectural application. Repeated moisture absorption and desorption may influence dimensional stability, mechanical integrity, and the consistency of responsive behaviour. Depending on their composition, fabrication methods, and environmental exposure conditions, bio-inspired façade materials may be susceptible to biological deterioration, ultraviolet degradation, mechanical fatigue, and reduced functional performance under prolonged environmental stress. These potential limitations highlight the importance of evaluating material properties, mechanical behaviour, and environmental responsiveness before their widespread architectural application [87,88]. Furthermore, the transition from laboratory-scale prototypes to commercially viable façade components may be constrained by manufacturing costs, limited material standardisation, production scalability, and uncertainties surrounding regulatory compliance. Recent research on the industrialisation of biomimetic design highlights the importance of advanced manufacturing technologies, production feasibility, and scalability in translating biological design principles into practical engineering applications [88–90]. Consequently, future material development should prioritise accelerated ageing tests, repeated environmental exposure assessments, long-term mechanical characterisation, and comparative life-cycle assessments to establish the durability, environmental performance, and practical feasibility of bio-inspired façade materials under actual operating conditions [89,90].

Dynamic shading systems constitute a further category of adaptive façade technologies designed to regulate solar radiation, daylight penetration, glare, and heat gain in response to changing environmental conditions. Unlike conventional static shading devices, dynamic façade systems incorporate movable elements, responsive materials, sensors, or automated control mechanisms that enable building-envelope components to adjust their configurations or properties in response to solar position, outdoor temperature, and indoor environmental requirements [42,60,79,91–93]. These technologies may improve daylight utilisation, reduce cooling loads, and enhance visual and thermal comfort through more precise regulation of solar radiation and heat transfer [42,60,79,92,93]. Their performance potential is consistent

with studies examining sustainable façade strategies, responsive glazing technologies, and the integration of intelligent systems to optimise building energy performance [60,79,91–94].

Despite these advantages, dynamic shading technologies present important economic and operational challenges. The incorporation of actuators, motors, sensors, control units, and specialised mechanical components can increase initial construction costs and require additional expenditure for installation, commissioning, and system integration. Moreover, repeated mechanical movement and prolonged exposure to wind, dust, moisture, and temperature fluctuations may contribute to component deterioration, actuator malfunction, and increased maintenance requirements. These challenges are particularly relevant to complex kinetic façade systems, where operational reliability depends on the coordinated functioning of mechanical assemblies and intelligent control technologies [16,60,76,95–98]. In addition, malfunctioning sensors, inadequate calibration, or poor integration with building-management systems may compromise shading effectiveness and occupant comfort. Accordingly, practical implementation should incorporate robust mechanical design, accessible maintenance arrangements, reliable control strategies, and appropriate manual override mechanisms to improve long-term operational performance [8,18,50].

Beyond the technical characteristics of individual smart materials, the economic feasibility of adaptive façades remains an important determinant of their adoption in architectural practice. Advanced materials, specialised fabrication processes, automated components, and intelligent monitoring systems may require substantially greater initial investment than conventional building-envelope technologies. Although these investments may be partially offset by operational energy savings, their financial viability depends on local energy prices, climatic conditions, building occupancy, maintenance expenditure, component replacement cycles, and expected service life. Research addressing the technological readiness, scalability, and implementation barriers of biomimetic innovations highlights the importance of considering these practical constraints during architectural design and technology selection [16,18,26]. Therefore, lifecycle cost analysis should accompany energy-performance simulations to establish whether projected savings can justify the additional capital and operational expenditures.

Maintenance complexity also represents a critical challenge, particularly where adaptive façades integrate mechanical, electronic, and biological components. Kinetic systems require periodic inspection and servicing of moving elements, actuators, and sensors, whereas bio-adaptive technologies may require specialised biological monitoring and environmental management. For example, microalgae-based façade systems offer opportunities for biomass production, solar regulation, and thermal-performance enhancement [12]. However, their implementation introduces requirements relating to water circulation, nutrient supply, biological stability, cleaning, and the integration of photobioreactor components with conventional building services [41]. Similarly, vegetated façade systems require appropriate irrigation, plant maintenance, and monitoring to sustain their environmental functions [5,32,48,99]. These operational demands demonstrate that the sustainability of adaptive façade systems cannot be assessed solely through their theoretical energy-saving potential but must also account for the resources and technical expertise required to maintain their functionality.

From an environmental perspective, the incorporation of smart materials into adaptive façades should be evaluated through comprehensive lifecycle assessment rather than operational energy performance alone. The extraction and processing of raw materials, component manufacturing, transportation, installation, maintenance, and end-of-life management may generate embodied carbon emissions and additional environmental burdens. Consequently, reductions in operational energy consumption do not necessarily guarantee lower overall environmental impacts, particularly where advanced systems require

frequent replacement or energy-intensive manufacturing processes. Studies examining biomimetic strategies for sustainable construction, circular-economy principles, and bio-inspired material systems emphasise the importance of integrating material efficiency, resource conservation, durability, and life-cycle considerations into architectural design and decision-making. These approaches offer opportunities to reduce material consumption, improve resource utilisation, and support the development of more environmentally responsible building systems, although their sustainability benefits require evaluation across the entire material and building life cycle [5,32,48,56,63,100–106].

The principal smart materials and responsive mechanisms identified in this review are summarised in Supplementary Table S8, while Supplementary Table S9 presents their potential contributions to energy efficiency, occupant comfort, and environmental sustainability. Collectively, these technologies demonstrate how biomimetic principles can support the development of more responsive and environmentally adaptable building envelopes. However, the effectiveness and long-term sustainability of biomimetic building systems remain dependent on material characteristics, climatic suitability, technological integration, operational and maintenance requirements, and economic feasibility. Consequently, their practical application requires comprehensive performance evaluation, appropriate material selection, and consideration of life-cycle costs and environmental impacts [10,16,48,63,86]. Furthermore, the reported performance benefits should be interpreted as context-specific findings derived from heterogeneous research designs rather than generalisable estimates of technological effectiveness. The absence of formal study-level risk-of-bias and evidence-certainty assessments further limits definitive comparisons among the reviewed technologies. Broader discussions of energy-efficient tall-building design, building-integrated photovoltaics, the relationship between buildings and public space, and biomimicry technologies provide additional architectural context for evaluating such systems [107–110].

Overall, smart-material adaptive façades provide promising opportunities for advancing sustainable architecture through passive environmental regulation, responsive shading, improved thermal performance, and resource-efficient material innovation. Nevertheless, the transition from experimental development to widespread architectural application requires a balanced evaluation of theoretical benefits and practical implementation challenges. Future research should therefore prioritise long-term field monitoring, accelerated material ageing tests, actuator reliability assessments, post-occupancy evaluations, life-cycle cost analysis, and comparative environmental assessments. Such investigations are essential for establishing the technical reliability, economic viability, environmental effectiveness, and scalability of adaptive façade technologies across different building typologies and climatic contexts. Existing research on dynamic façade optimisation, smart materials, biomimetic kinetic shading systems, and the industrial scalability of bio-inspired technologies provides a foundation for these future investigations [42,72,86,89].

Table 3. Summary of the Study's Findings on Diverse Existing Innovations in Adaptive Facades.

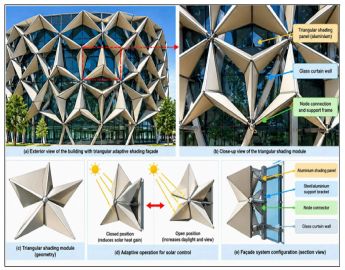
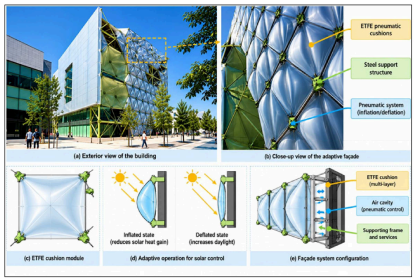
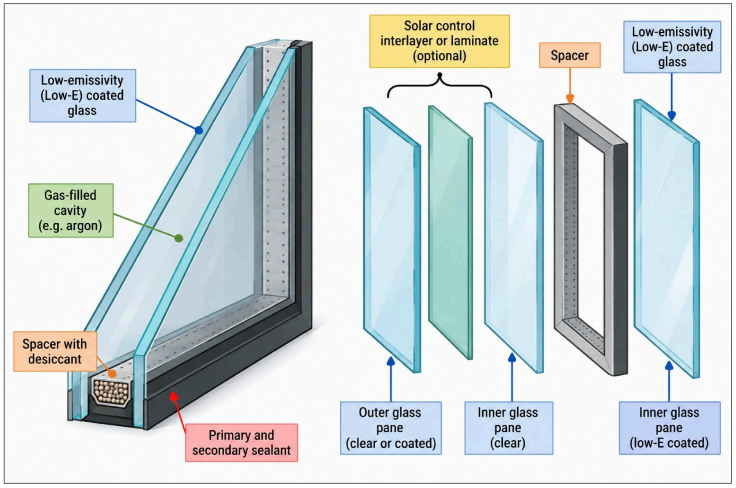
Adaptive Façade Innovation	Description and Operating Principles	Architectural Examples and Applications	Potential Sustainability and Performance Benefits	Illustrations and Image Attribution & Supporting References
1. Kinetic Facades	Kinetic facades use moving components to adapt to environmental conditions, such as sunlight, wind, or temperature. These components can rotate, slide, or fold to regulate light, ventilation, and shading.	(i) Al Bahar Towers (Abu Dhabi): Features a lattice-like facade with motorised elements that open and close to reduce solar heat gain. (ii) Media-TIC Building (Barcelona): Incorporates pneumatic cushions that inflate or deflate based on sunlight intensity to control interior temperatures.	Dynamic control over solar shading and ventilation, reducing energy consumption and improving user comfort.	 Al Bahar Towers (Abu Dhabi) [77].  Media-TIC Building (Barcelona) [107]
2. Smart Materials	Smart materials embedded in facades change their properties in response to environmental stimuli such as temperature, light, or humidity	(i) Thermochromic Glass: Changes transparency based on temperature, reducing glare and solar heat gain (ii) Electrochromic Glass: Adjusts tint levels when an electrical charge is applied, offering customizable shading (iii) Phase Change Materials (PCMs): Store and release thermal energy by transitioning between solid and liquid states, stabilising interior temperatures.	Improved energy efficiency, reduced reliance on mechanical HVAC systems, and enhanced daylight control.	 Thermochromic smart glass [87]

Table 3. *Cont.*

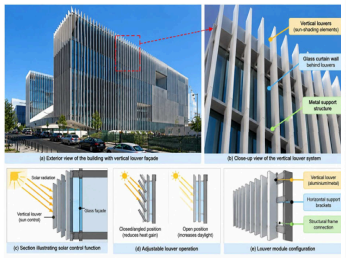
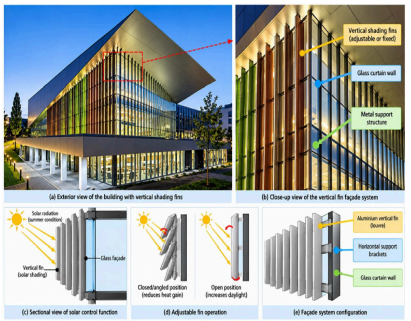
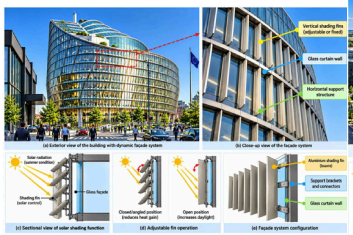
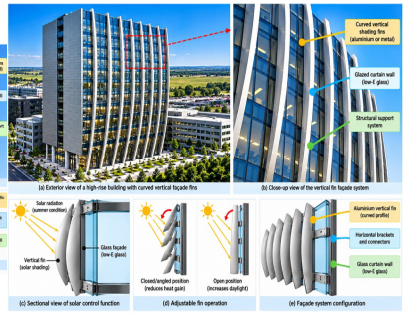
Adaptive Façade Innovation	Description and Operating Principles	Architectural Examples and Applications	Potential Sustainability and Performance Benefits	Illustrations and Image Attribution & Supporting References
3. Photovoltaic (PV) Facadess	Integrating solar panels into the facade enables the building to generate renewable energy. PV panels can be rigid or flexible; some designs double as shading elements.	(i)The Edge (Amsterdam): Incorporates PV cells on the facade to power building systems (ii)SwissTech Convention Centre (Lausanne): Features bifacial PV panels that generate electricity from both direct sunlight and reflected light.	Reduced carbon footprint, energy independence, and alignment with net-zero building goals.	 The Edge (Amsterdam) [108].  SwissTech Convention Centre (Lausanne) [87].
4. Double-Skin Facades (DS	F)DSFs consist of two layers of glass with an air cavity in between, which acts as a thermal buffer and can be ventilated naturally or mechanically.	(i) One Angel Square (Manchester): Combines DSF with an energy-efficient ventilation system s.(ii) Copenhagen Towers (Denmark): Uses DSF for passive heating and cooling.	Improved thermal performance, noise reduction, and natural ventilation.	 One Angel Square [94].  Copenhagen Towers [109].

Table 3. *Cont.*

Adaptive Façade Innovation	Description and Operating Principles	Architectural Examples and Applications	Potential Sustainability and Performance Benefits	Illustrations and Image Attribution & Supporting References
5. Bio-Adaptive Faca	desThese facades incorporate living organisms or biological materials that react to environmental chang	es.(i) BIQ House (Hamburg): Features a facade with microalgae panels that produce biomass and energy while providing shadi ng.(ii) Living Walls: Incorporate vegetation to improve air quality and thermal insulation.	Enhanced air quality, energy production, and integration with nature.	 BIQ House [9].  Living Walls [4].
6. Intelligent Control Syst	emsAdvanced facades integrate sensors, actuators, and AI-driven systems to monitor and respond to environmental conditions in real-time.	(i) The Crystal (London): Uses intelligent controls to adjust shading and ventilation based on weather da ta.(ii) Facade Control Systems: Combine data from sensors monitoring sunlight, wind, and temperature to automate adjustments.	Real-time optimisation of energy usage, increased user comfort, and seamless operation.	 The Crystal [68,110].  Galleria Centercity [100].

4. Conclusions and Recommendation

This systematic review synthesised the application of biomimetic principles in architectural and building-envelope design through a five-dimensional analytical framework encompassing nature as form, process, system, material, and adaptation. The framework's principal contribution lies in integrating established biomimetic classification approaches into a coherent analytical structure that distinguishes biological morphology, functional processes, systemic interactions, material properties, and adaptive responses. By establishing clearer conceptual boundaries among these dimensions, the framework facilitates identifying predominant biomimetic strategies in the reviewed studies and clarifies how biological principles translate into architectural applications and associated building-performance objectives. Furthermore, it provides a structured basis for interpreting heterogeneous research findings in relation to environmental performance and sustainable building design. The conclusions are organised according to the four research questions, with particular attention to differences in the strength and nature of the available evidence, including conceptual investigations, computational simulations, experimental studies, and real-world architectural applications.

For RQ1 on the principal biomimetic strategies in architectural and building design, this review identified five recurring biomimetic strategies: nature as form, nature as process, nature as system, nature as material, and nature as adaptation. Nature as form encompasses the translation of biological geometries, structural configurations, and morphological patterns into architectural components. Nature as process concerns the application of biological functions and mechanisms, including passive thermal regulation, moisture responsiveness, and environmental exchange. Nature as system considers the relationships among biological components and processes as models for integrated architectural and environmental design. Nature as material focuses on bio-inspired and bio-based materials, including responsive composites, self-healing systems, and resource-efficient construction materials. Nature as adaptation addresses the capacity of building envelopes to respond to variations in temperature, solar radiation, humidity, and other environmental conditions. These five dimensions provide a thematic classification of the reviewed literature rather than a ranking of technological effectiveness. Their identification is supported by the qualitative synthesis of the included studies, although the extent of empirical validation differs across individual applications. The framework also indicates that biomimetic strategies may overlap, particularly where biological form, material properties, and adaptive mechanisms are integrated within the same building-envelope system.

Also, in connection with RQ2 exploring the study's contributions to building performance for biomimetic architectural strategies, this review reports potential contributions of biomimetic strategies to thermal regulation, solar control, daylight utilisation, ventilation, material efficiency, and occupant comfort. In particular, adaptive façades and dynamic shading systems are associated with opportunities to regulate solar exposure and indoor environmental conditions, while bio-inspired materials offer possibilities for passive responsiveness and alternative material applications. However, the strength of this evidence varies considerably. Some findings are derived from numerical simulations and computational optimisation, others from laboratory-scale experiments and prototype investigations, and a smaller body of evidence concerns operational applications in buildings. Consequently, the reported performance outcomes should be interpreted within their respective climatic, technological, and methodological contexts. The heterogeneity of performance indicators, experimental conditions, and assessment methods limits direct comparison among technologies. Furthermore, the review did not conduct a quantitative meta-analysis or formal evidence-certainty assessment. It therefore cannot establish pooled performance effects

or determine which biomimetic strategy is consistently superior across different building types and environmental conditions.

Regarding RQ3 on what opportunities and practical challenges influence the architectural application of biomimetic strategies, the synthesis identifies adaptive building envelopes, responsive materials, passive environmental control, and integrated façade systems as prominent areas of architectural application. Nevertheless, the discussion in Sections 3.8 and 3.9 indicates that practical implementation involves several technical, economic, and operational constraints. These include high initial capital costs, the mechanical complexity of kinetic shading systems, actuator maintenance, sensor calibration, system interoperability, and uncertainties regarding the long-term durability of bio-based and hygroscopic materials. Additional concerns relate to material scalability, environmental exposure, specialised maintenance requirements, component replacement, and the lifecycle impacts of advanced façade technologies. Although simulation and prototype studies provide useful indications of technical potential, they do not necessarily establish long-term reliability or economic feasibility under normal building operating conditions. The review therefore suggests that the architectural applicability of biomimetic innovations depends on the interaction between environmental performance, material properties, maintenance capacity, financial considerations, and local climatic requirements. These conclusions are supported primarily by the thematic interpretation of the reviewed studies and should not be understood as a quantified assessment of implementation barriers across the construction industry.

For RQ4 exploring what patterns, gaps, and future research directions emerge from the application of biomimetic principles in architectural design, four broad patterns emerge from the synthesis. First, the literature increasingly considers biological adaptation and environmental responsiveness as conceptual foundations for architectural innovation. Second, computational modelling, digital fabrication, and intelligent control technologies provide opportunities to translate biological principles into building-envelope applications. Third, research approaches and performance indicators remain heterogeneous, making direct comparisons difficult. Fourth, a distinction persists between the potential identified through conceptual, computational, and laboratory investigations and the evidence available from long-term operational building assessments.

The principal research gaps concern the limited comparability of reported performance outcomes, insufficient long-term durability evidence, incomplete lifecycle cost and environmental assessments, and the need for more systematic evaluation of occupant experiences and operational reliability. These gaps are particularly relevant to kinetic façade mechanisms, hygroscopic materials, bio-based composites, and biologically integrated building systems. The five-dimensional framework provides a basis for organising these research priorities, although its applicability and explanatory value would benefit from further testing across different architectural contexts.

5. Recommendations and Future Research Priorities

Based on the findings and limitations of the review, six recommendations are proposed:

i. **Integrate biomimetic strategies with computational modelling and optimisation**. The reviewed applications of adaptive façades and environmentally responsive systems provide a basis for investigating the integration of biological principles with parametric modelling, building-performance simulation, artificial intelligence, and multi-objective optimisation. Future studies could compare bio-inspired design alternatives using consistent indicators for thermal performance, energy consumption, daylighting, ventilation, and occupant comfort. This recommendation is primarily informed by computational and design-oriented evidence rather than established comparative field performance.

ii. **Develop climate-responsive and context-specific applications:** The reported performance of adaptive shading, thermoregulating skins, and moisture-responsive materials suggests that biomimetic solutions should be evaluated in relation to local solar conditions, temperature variations, humidity, building orientation, and occupancy patterns. Comparative investigations across different climatic regions would help establish the transferability of reported findings. The supporting evidence is context-dependent and does not establish universal suitability across building typologies.

iii. **Expand experimental validation and long-term field monitoring***:* The methodological diversity of the reviewed studies indicates a need for laboratory investigations, prototype testing, full-scale measurements, and longitudinal post-occupancy assessments. Particular attention could be directed towards operational energy consumption, indoor temperature, daylight availability, thermal comfort, ventilation effectiveness, actuator reliability, and material degradation. This recommendation responds to the identified limitations of simulation-based and short-duration experimental evidence.

iv. **Evaluate the reliability and usability of intelligent façade systems:** Studies addressing dynamic shading and adaptive controls indicate opportunities for integrating environmental sensors, actuators, and automated management systems. Future research could assess control accuracy, maintenance frequency, mechanical reliability, interoperability, occupant satisfaction, and manual override arrangements under operational conditions. Such assessments would help clarify whether reported environmental benefits remain achievable throughout the service life of the systems.

v. **Strengthen interdisciplinary collaboration and implementation research:** The five-dimensional framework brings together biological, architectural, material, environmental, and technological considerations. Collaboration among architects, biologists, engineers, material scientists, manufacturers, and computational researchers could support the translation of biological concepts into testable architectural applications. Research could also examine manufacturing feasibility, regulatory compliance, maintenance requirements, and lifecycle costs. This recommendation follows from the interdisciplinary nature of the reviewed approaches and the practical barriers identified in Sections 3.8 and 3.9.

vi. **Establish comparable performance indicators and evidence-assessment procedures:** The heterogeneity of the reviewed literature limits reliable comparisons between biomimetic and conventional building-envelope technologies. Future investigations could adopt common reporting indicators covering operational energy, thermal and visual comfort, embodied environmental impacts, material durability, maintenance expenditure, and lifecycle costs. Where appropriate, comparative studies should incorporate reference cases, clearly defined measurement periods, transparent assumptions, and uncertainty analyses. Subsequent systematic reviews could also apply formal risk-of-bias and evidence-certainty assessment procedures to distinguish well-supported findings from preliminary technological claims.

In conclusion, the review offers a five-dimensional framework for interpreting biomimetic strategies in architectural design and identifies their reported relationships with building performance, environmental responsiveness, and sustainable material development. Its contribution is primarily conceptual and synthesising, rather than an empirical verification of the comparative effectiveness of individual technologies. The findings indicate promising directions for further investigation while also revealing limitations in the consistency, duration, and comparability of the available evidence. Future research incorporating standardised assessments, long-term operational measurements, durability investigations, and lifecycle evaluations could provide a stronger basis for determining the practical effectiveness and scalability of biomimetic architectural applications.

6. Practical Implications of the Study

- Interdisciplinary collaboration: Architects, façade engineers, biologists, material scientists, computational designers, and manufacturers should collaborate to translate biological principles into technically viable façade solutions. The wider literature also frames ecological coexistence as a complex sustainability objective and explores regenerative buildings as components of their surrounding ecosystems [111,112].
- From inspiration to function: Biomimetic design should move beyond reproducing natural forms and instead translate biological functions, processes, materials, systems, and adaptive mechanisms into measurable architectural performance.
- Design and performance evaluation: The five-dimensional framework nature as form, process, system, material, and adaptation can guide the selection of biological analogues and façade strategies. These strategies should be evaluated using measurable indicators such as thermal performance, energy demand, daylighting, ventilation, moisture regulation, and thermal comfort.
- Manufacturability and maintenance: Proposed systems should be assessed for structural integrity, fabrication, installation, weather resistance, fire safety, durability, maintenance requirements, component replacement, and compatibility with existing building systems.
- Economic and environmental feasibility: Biomimetic technologies may involve higher initial costs because of specialised materials, sensors, actuators, or fabrication processes. Their viability should therefore be assessed through life-cycle costing and environmental assessment, considering operational energy, embodied impacts, durability, maintenance, and replacement.
- Climatic responsiveness: Biomimetic strategies should be adapted to local climatic conditions. A solution developed for a hot-arid climate may not produce comparable results in humid tropical, temperate, Mediterranean, or cold environments. Solar exposure, temperature, humidity, wind, rainfall, orientation, and occupancy should therefore inform design decisions. Related building-services research examines air-conditioner efficiency in Malaysia, ground-source heat pumps for space cooling in Southeast Asia, and advances in air-conditioning technologies; these studies provide contextual comparisons rather than direct evidence of biomimetic façade performance [113–115].

7. Limitations and Future Study

Despite the systematic approach adopted for this review, a number of limitations should be acknowledged. Firstly, whereas the search strategy encompassed Scopus, Web of Science, ScienceDirect, and Google Scholar, the absence of formally documented dated database specific search strategies and independently verifiable records of database specific retrieval undermines processes of replication and audit trails; the restriction to English publications dated 2021–2026 runs the risk of excluding publications in other languages or outside of this temporal window, introducing language/publication-period biases.

Secondly, the number of reviewers involved in the study screening, data extraction, and methodological appraisal processes, the extent to which independent assessments were undertaken, and the methods by which disagreements were resolved were inadequately documented. Consequently, the uniformity of eligibility decision-making or thematic categorisation cannot be independently assessed; although 109 bibliographic entries were collated, a number of these records remain to be verified in terms of their duplication status, eligibility, and alignment with the inclusion/exclusion criteria, meaning that the 109 reported included studies remain subject to final reconciliation, potentially impacting on reported descriptive frequencies or thematic distributions.

Thirdly, neither a formal study-level risk of bias assessment, certainty of evidence assessment, nor systematic reporting bias analysis was undertaken. As such, an evaluation of the degree to which the methodological rigour of the included evidence impacts upon the confidence in the estimated effects or findings reported in relation to improved building energy efficiency, thermal performance, material sustainability, or environmental adaptation is absent; methodological heterogeneity in the experimental investigations, simulation-based analyses, conceptual models or architectural case studies included in this review precluded the use of a quantitative meta-analytical approach, restricting the synthesis process to descriptive and thematic comparisons only.

Finally, the proposed five-dimensional biomimetic framework merely provides a descriptive interpretation of the published literature, and its capacity to predict findings in relation to different climatic zones, building typologies, materials, or operational conditions remains to be established. Future systematic reviews should adopt more prospectively documented search strategies, independent reviewer screening and data extraction processes, verify study-level datasets, undertake standardised methodological quality assessment protocols, and utilise transparent evidence-synthesis methodologies to enhance the reliability and applicability of their research findings.

Overall, future research should be focused on the experimental verification of biomimetic façade performance and its sustainability under real operating conditions and the subsequent analysis with computer simulations. The comparative assessments should be made for different climatic regions, building typologies, specific types of façades, and biomimetic approaches to understand the influence of external factors on their performance. Research should also be concerned with the necessary development of bio-inspired materials, structural elements, and computer algorithms to facilitate the implementation at a large scale, manufacturing adaptability, and overall sustainability of biomimetic solutions. Particular attention should be paid to the maintenance, reliability, and functionality of biomimetic systems and structures. The governance implications of ecological design may also be considered alongside scholarship on rights-of-nature policies, while recognising that such work does not directly establish façade performance outcomes [116].

Life-cycle assessment and cost–benefit analyses should be done to evaluate the energy performance, embodied impacts, construction costs, maintenance, repair, replacement, and end-of-life scenarios of different types of biomimetic façades. Furthermore, the role of occupants in the context of biomimetic solutions should be explored to assess their comfort and potential benefits. Finally, a study should be conducted to identify how the biomimetic approach could be implemented in different socioeconomic and cultural settings and what benefits such an approach might bring to the economy, environment, and society. This research would allow us to identify the biomimetic design areas that need improvement and better contextual adaptability.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings16214367/s1, Table S1: PRISMA 2020 checklist; Table S2: PRISMA 2020 for Eligibility and Verification Assessment of Reference Entries (Years 2021 and 2026 periods); Table S3: Data Extraction and Coding Framework for the Reviewed Studies; Table S4: Phases of thematic research applied to classify biomimetic design principles; Table S5: Application-Level Classification of Biomimetic Architectural Studies; Table S6: Five-Dimensional Biomimetic Architectural Framework; Table S7. Comparative synthesis of biomimetic principles, architectural strategies and documented performance outcomes; Table S8: Smart Materials in Adaptive Facades; Table S9: Contributions of Adaptive Façades to Energy Efficiency, User Comfort, and Sustainability; Figure S1: Bosco Verticale, Italy. (a) External view of Verticale; (b) Detailed façade view; (c) Environmental performance diagram; (d) Sectional and seasonal analysis of the building; Figure S2: Al Bahar Towers in Abu Dhabi. (a) Overall view of Al Bahar Towers; (b) Close-up of the

dynamic triangular shading modules (mashrabiya-inspired façade panels); (c). Digital parametric modelling and geometric transformation process; (d) Exploded axonometric representation.

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Abbreviations

The following abbreviations are used in this manuscript:

BA	Biomimicry in Architecture
BFD	Biomimetic Façade Design
CRBT	Climate-Responsive Building Technologies
DSFs	Double-Skin Façades
HVAC	Heating, Ventilation, and Air Conditioning
PCMs	Phase Change Materials
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PV	Photovoltaic
SLR	Systematic Literature Review

References

1. Pawlyn, M. *Biomimicry in Architecture*, 3rd ed.; RIBA Publishing: London, UK, 2025.
2. Metwally, W.M. Biomimicry and green architecture: Nature-inspired innovations for sustainable buildings. *Sustainability* **2025**, *17*, 7223. [CrossRef]
3. Quoc Toan, N.; Phuong, N.T.K.; Van Tam, N.; Quoc Viet, L. From Biomimicry to Climate-Responsive Architecture: Prioritising Bio-Based and Bio-Inspired Strategies for Sustainable Buildings in Tropical Monsoon Climates. *Buildings* **2026**, *16*, 771. [CrossRef]
4. Wang, X.; Xiao, L.; Fan, L.; Mokhtar, N.A.; Mat Sulaiman, M.K.A. Application of bionic architecture in low-carbon design: A systematic review from nature inspiration to architectural practice. *Front. Built Environ.* **2025**, *11*, 1652481. [CrossRef]
5. Pacios-Álvarez, A.; Fogaça, D.R.; Ordier-es-Meré, J.; Vizier, E. Biomimetic approaches for carbon neutrality in construction: A systematic review of nature-inspired solutions across the life cycle. *Clean Technol. Environ. Policy* **2026**, *28*, 129. [CrossRef]
6. Imani, N.; Vale, B. Biomimetic Design for Building Energy Efficiency 2021. *Biomimetics* **2022**, *7*, 106. [CrossRef]
7. Chaudhary, S.; Singh, R.; Zore, A.S.; Upadhyay, A.; Lindenberger, C.; Vivekanand, V. Bio-inspired technology in society: Ethical and architectural innovations for sustainable development. *Technol. Soc.* **2024**, *78*, 102688. [CrossRef]
8. Jalali, S.; Badarnah, L. A biomimetic design framework for adaptive solar building envelopes: Integrating solar adaptation factors, performance development, and decision support. *Build. Environ.* **2026**, *301*, 114765. [CrossRef]
9. Ashraf, N.; Abdin, A.R. Biomimetic design synthesis and digital optimisation of building shading skin: A novel conceptual framework for enhanced energy efficiency. *Energy Build.* **2024**, *323*, 114824. [CrossRef]
10. Bagheri Moghaddam, F.; Bakhshoodeh, R.; Banihashemi, S. From nature to structure: Advancing building efficiency with biomimicry-inspired green façades. *Smart Sustain. Built Environ.* **2025**, 1–24. [CrossRef]
11. Mohamed, A.S.; Binabid, J. Synergising Nature-Inspired Adaptive Facades: Harnessing Plant Responses for Elevated Building Performance in Alignment with Saudi Green Initiatives. *Buildings* **2025**, *15*, 3878. [CrossRef]
12. Talaei, M.; Mahdavinejad, M.; Azari, R.; Haghighi, H.M.; Atashdast, A. Thermal and energy performance of a user-responsive micro-algae bioreactive façade for climate adaptability. *Sustain. Energy Technol. Assess.* **2022**, *52*, 101894. [CrossRef]

13. Ahmadizadeh, M.; Heidari, M.; Thangavel, S.; Khashehchi, M.; Rahmanivahid, P.; Singh, V.P.; Kumar, A. Development of new materials for sustainable buildings. In *Sustainable Technologies for Energy Efficient Buildings*; CRC Press: Boca Raton, FL, USA, 2024; pp. 30–48.
14. Hu, P.; Hu, X.; Liu, L.; Li, M.; Zhao, Z.; Zhang, P.; Wang, J.; Sun, Z. Dimensional upgrading of 0D silica nanospheres to 3D networking toward robust aerogels for fire resistance and low-carbon applications. *Mater. Sci. Eng. R Rep.* **2024**, *161*, 100842. [CrossRef]
15. Balkis, M.M.; Atakara, C. Biomimetic strategies for climate-adaptive buildings: A multi-case analytical framework linking biological mechanisms, architectural translation, and evidence status. *Biomimetics* **2026**, *11*, 711. [CrossRef]
16. Ghoneim, R.S.; Arabasy, M.; Abdulhadi, A.N. AI-driven optimisation of indoor environmental quality and energy consumption in smart buildings: A bio-inspired algorithmic approach. *J. Asian Archit. Build. Eng.* **2026**, *25*, 1089–1113. [CrossRef]
17. Gholami, H.; Sangin, H.; Taghizadeh, K.; Yazdi Bahri, S.; Alier Forment, M. Biomimetic adaptive façades for integrated energy, daylight, and water performance in semi-arid climates. *Energy Rep.* **2026**, *16*, 109591. [CrossRef]
18. Ruwanpura, J. Biomimicry in building design and construction: A framework to address technical, economic, and regulatory challenges. In *Proceedings of the Construction Research Congress 2026, San Antonio, TX, USA, 18–21 March 2026*; American Society of Civil Engineers: Reston, VA, USA, 2026; pp. 429–439. [CrossRef]
19. Sajadirad, F.; Masoumi, S.; Mastouri, R. Designing sustainable and energy-efficient buildings through biomorphic and climatic architectural strategies. *Int. J. Sustain. Dev. Goals* **2025**, *1*, 99–143. [CrossRef]
20. Ilieva, L.; Ursano, I.; Traista, L.; Hoffmann, B.; Dahy, H. Biomimicry as a sustainable design methodology—Introducing the 'Biomimicry for Sustainability' framework. *Biomimetics* **2022**, *7*, 37. [CrossRef]
21. Rahubadda, R.V.A.D.; Kulatunga, U. Development of a new definition for biomimicry in the field of net-zero construction. *Constr. Innov.* **2025**, *26*, 2628–2658. [CrossRef]
22. Mohammed, A.B. A systematic design technique of biomimicry to correlate and integrate architecture and biology to attain green buildings. *J. Eng. Sci.* **2023**, *51*, 239–259. [CrossRef]
23. Chakraborty, S.; Bera, D.; Roy, L.; Ghosh, C.K. Biomimetic and bioinspired nanostructures: Recent developments and applications. In *Bioinspired and Green Synthesis of Nanostructures: A Sustainable Approach*; Wiley: Hoboken, NJ, USA, 2023; pp. 353–404. [CrossRef]
24. Dixit, S.; Stefańska, A. Bio-logic: A review on the biomimetic application in architectural and structural design. *Ain Shams Eng. J.* **2023**, *14*, 101822. [CrossRef]
25. Jareed, M.B.E.; Kurt, S. Quantifying the energy performance of biomimetic façade systems in hot–arid residential buildings: A Libyan case study. *Buildings* **2026**, *16*, 3944. [CrossRef]
26. Valinejadshoubi, M.; Athienitis, A.K.; Bagchi, A.; Abtahi, M. Integrated dynamic photovoltaic facade for enhanced building comfort and energy efficiency. *Biomimetics* **2024**, *9*, 463. [CrossRef]
27. Salama, M.; Shahda, M.M.; Eltarabily, S.; Megahed, N.A. Biomimetic self-shading buildings: An analytical approach to improving environmental performance in hot and dry climates. In *Proceedings of the 5th International Symposium in Environmental Science and Industrial Ecology*; Springer Nature: Singapore, 2025; pp. 100–116. [CrossRef]
28. Wood, D.; Cheng, T.; Tahouni, Y.; Menges, A. Material programming for bio-inspired and bio-based hygromorphic building envelopes. In *Advanced Materials in Smart Building Skins for Sustainability: From Nano to Macroscale*; Wang, J., Shi, D., Song, Y., Eds.; Springer International Publishing: Cham, Switzerland, 2023; pp. 99–112. [CrossRef]
29. Sadegh, S.O.; Haile, S.G.; Jamshidzehi, Z. Development of two-step biomimetic design and evaluation framework for performance-oriented design of multi-functional adaptable building envelopes. *J. Daylighting* **2022**, *9*, 13–27. [CrossRef]
30. Webb, M. Biomimetic building facades demonstrate potential to reduce energy consumption for different building typologies in different climate zones. *Clean Technol. Environ. Policy* **2022**, *24*, 493–518. [CrossRef]
31. Möller, M.; Speck, T.; Speck, O. Sustainability assessments inspired by biological concepts. *Technol. Soc.* **2024**, *78*, 102630. [CrossRef]
32. Goyes-Balladares, A.; Moya-Jiménez, R.; Molina-Dueñas, V.; Chaca-Espinoza, W.; Magal-Royo, T. What inspires biomimicry in construction? Patterns, trends, and applications. *Biomimetics* **2025**, *10*, 259. [CrossRef]
33. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [CrossRef]
34. Rethlefsen, M.L.; Kirtley, S.; Waffenschmidt, S.; Ayala, A.P.; Moher, D.; Page, M.J.; PRISMA-S Group. PRISMA-S: An extension to the PRISMA statement for reporting literature searches in systematic reviews. *Syst. Rev.* **2021**, *10*, 39. [CrossRef]
35. Chairiyah, R. Biomimicry architecture for healthy built environment: A review of existing literature. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1218*, 012027. [CrossRef]
36. Sommese, F. Biomimetic Climate-Adaptive Building Envelopes: Mapping Research Trends and Assessing Technology Readiness Towards Real-World Implementation. *Buildings* **2026**, *16*, 2970. [CrossRef]

37. Khosromanesh, R. Towards refining bio-inspired hydro-actuated building facades by emphasising the importance of hybrid adaptability. *Sustainability* **2024**, *16*, 959. [CrossRef]
38. Verbrugghe, N.; Rubinacci, E.; Khan, A.Z. Biomimicry in architecture: A review of definitions, case studies, and design methods. *Biomimetics* **2023**, *8*, 107. [CrossRef]
39. Ridder, H.-G. Case study research: Approaches, methods and contributions to theory. In *The Oxford Handbook of Qualitative Research*, 2nd ed.; Oxford University Press: Oxford, UK, 2022.
40. Xiao, Y.; Watson, M. Guidance on conducting a systematic literature review. *J. Plan. Educ. Res.* **2019**, *39*, 93–112. [CrossRef]
41. Shahamat, H. Advancing bio-integrated building systems: A systematic review of architectural, structural and mechanical–electrical challenges in photobioreactor façades. *Smart Sustain. Built Environ.* **2025**, 1–32. [CrossRef]
42. Akimov, L.; Bezborodov, A.; Badenko, V. Example-based dynamic façade design using the façade daylighting performance improvement (FDPI) indicator. *Build. Simul.* **2023**, *16*, 2261–2283. [CrossRef]
43. Maguire, M.; Delahunt, B. Doing thematic analysis: A practical, step-by-step guide for learning and teaching scholars. *All Irel. J. High. Educ.* **2022**, *14*, 1–14.
44. Del, M.D.L.Á.O.; Beermann, K.; Austin, M.C. Environmentally responsive materials for building envelopes: A review on manufacturing and biomimicry-based approaches. *Biomimetics* **2023**, *8*, 52. [CrossRef]
45. Rahubadda, R.V.A.D.; Manewa, A.; Anagal, V.; Siriwardena, M. The Wood Wide Web as a blueprint for carbon-neutral cities: A biomimetic model for adaptive energy sharing. *Front. Built Environ.* **2025**, *11*, 1681714. [CrossRef]
46. Hubert, T.; Dugué, A.; Vogt Wu, T.; Bruneau, D.; Aujard, F. Exploiting the potential of nature for sustainable building designs: A novel bio-inspired framework based on a characterisation of living envelopes. In *Bionics and Sustainable Design*; Springer Nature: Singapore, 2022; pp. 289–331. [CrossRef]
47. Mfon, I.E.; Udoenang, D.O.; Udoh, S. Biomimicry as a framework for net-zero energy architecture in tropical climates: Advancing sustainable practices in design and performance. *J. Sustain. Archit. Pract.* **2025**, *15*, 44–59. [CrossRef]
48. Karuppusamy, M.; Palanisamy, S.; Gurusamy, M.; Balasubramanian, V.P.; Jayamani, M.; Sankar, S.L.; Sundararajan, K.; Sivanantham, G.; Ali, S.K.; Palaniappan, M.; et al. Biomimetic and bioinspired materials: Design strategies, mechanical properties, and engineering applications—A review. *Glob. Chall.* **2026**, *10*, e70101. [CrossRef]
49. Pawlyn, M. *Biomimicry in Architecture*, 2nd ed.; RIBA Publishing: London, UK, 2016.
50. Stephen, S.; Bello, J.O.; Aigbavboa, C.; Oke, A.E.; Ogunade, T. Bio-inspired cyber-physical systems for adaptive building performance: A simulation study integrating AI-driven control and digital twin concepts. *Smart Sustain. Built Environ.* **2026**, 1–20. [CrossRef]
51. Irene, N.J. Biomimicry: Designing sustainable solutions from nature. *IAA J. Biol. Sci.* **2025**, *13*, 75–80. [CrossRef]
52. Alyahya, A.; Lannon, S.; Jabi, W. A framework for optimising biomimetic opaque ventilated façades using CFD and machine learning. *Buildings* **2025**, *15*, 4130. [CrossRef]
53. Fallahpour, M.; Khorshidi, I.M.; Ghasempour, F.; Davari, D.D.; Khoei, E.T.; Tamimi, M. A multi-objective optimisation framework for designing a double-skin façade in a hot-arid climate: Central composite design and CFD simulation. *Results Eng.* **2025**, *25*, 104288. [CrossRef]
54. Sedira, N.; Pinto, J.; Ginja, M.; Gomes, A.P.; Nepomuceno, M.C.S.; Pereira, S. Investigating the architecture and characteristics of Asian hornet nests: A biomimetics examination of structure and materials. *Materials* **2023**, *16*, 7027. [CrossRef]
55. Ahamed, M.K.; Wang, H.; Hazell, P.J. From biology to biomimicry: Using nature to build better structures—A review. *Constr. Build. Mater.* **2022**, *320*, 126195. [CrossRef]
56. Antonini, E.; Boeri, A.; Giglio, F. Classification criteria and markers for biomimetic building envelope within circular economy principles: A critical review. *Archit. Eng. Des. Manag.* **2022**, *18*, 387–409. [CrossRef]
57. Singh, B.; Basri, A.A.; Yidris, N.; Pai, R.; Ah-mad, K.A. Introduction to biomimetics, modelling and analysis. In *High Performance Computing in Biomimetics: Modelling, Architecture and Applications*; Springer Nature: Singapore, 2024; pp. 1–20. [CrossRef]
58. AlAli, M.; Mattar, Y.; Alzaim, M.A.; Beheiry, S. Applications of biomimicry in architecture, construction and civil engineering. *Biomimetics* **2023**, *8*, 202. [CrossRef]
59. Fouad, F.H.; Youssef, K.A.; Ahmed, S.A.M. From Nature to Building Skins: Critical Review of Biomimetic Building Skin Research. *JES. J. Eng. Sci.* **2025**, *53*, 1–28. [CrossRef]
60. Faragalla, A.M.A.; Asadi, S. Biomimetic design for adaptive building façades: A paradigm shift towards environmentally conscious architecture. *Energies* **2022**, *15*, 5390. [CrossRef]
61. Penick, C.A.; Cope, G.; Morankar, S.; Mistry, Y.; Grishin, A.; Chawla, N.; Bhate, D. The comparative approach to bio-inspired design: Integrating biodiversity and biologists into the design process. *Integr. Comp. Biol.* **2022**, *62*, 1153–1163. [CrossRef]
62. Fattepur, G.; Patil, A.Y.; Kumar, P.; Kumar, A.; Hegde, C.; Siddhalingeshwar, I.G.; Khan, T.Y. Bio-inspired designs: Leveraging biological brilliance in mechanical engineering—An overview. *3 Biotech* **2024**, *14*, 312. [CrossRef]
63. Bras, A. Nature-inspired innovations: Bio-based materials for resilient buildings and structures. In *Proceedings of the RILEM Spring Convention*; Alderete, N.M., Debbaut, B., Zhang, Y., De Belie, N., De Schutter, G., Eds.; Springer Nature: Cham, Switzerland, 2026; Volume 1, pp. 11–20. [CrossRef]

64. Heil, N.; Perricone, V.; Gruber, P.; Guéna, F. Bioinspired, biobased and living material designs: A review of recent research in architecture and construction. *Bioinspiration Biomim.* **2023**, *18*, 041001. [CrossRef]
65. Sandak, A.; Butina Ogorelec, K. Bioinspired building materials—Lessons from nature. *Front. Mater.* **2023**, *10*, 1283163. [CrossRef]
66. Sagar, K.S.R.; Awasthi, A.; Dwivedi, S.P.; Shrivastava, M.; Pahwa, S.; Swathi, B.; Hlail, S.H. Smart resource management: An innovative way of balancing materials, energy, and waste for a green future. *E3S Web Conf.* **2023**, *453*, 01037. [CrossRef]
67. Buckton, S.J.; Fazey, I.; Sharpe, B.; Om, E.S.; Doherty, B.; Ball, P.; Sinclair, M. The Regenerative Lens: A conceptual framework for regenerative social-ecological systems. *One Earth* **2023**, *6*, 824–842. [CrossRef]
68. Choi, H.-S. Sustainable urban planning for high-rise residential complexes using an adaptive façade system. *Appl. Sci.* **2026**, *16*, 1574. [CrossRef]
69. Shi, X.; Shi, C.; Tablada, A.; Guan, X.; Cui, M.; Rong, Y.; Xie, X. A review of research progress in vertical farming on façades: Design, technology, and benefits. *Sustainability* **2025**, *17*, 921. [CrossRef]
70. Hays, N.; Badarnah, L.; Jain, A. Biomimetic design of building facades: An evolution-ary-based computational approach inspired by elephant skin for cooling in hot and humid climates. *Front. Built Environ.* **2024**, *10*, 1309621. [CrossRef]
71. Srisuwan, T. Applications of biomimetic adaptive facades for enhancing building energy efficiency. *Int. J. Build. Urban Inter. Landsc. Technol.* **2022**, *20*, 7–18. [CrossRef]
72. Brzezicki, M. A systematic review of the most recent concepts in kinetic shading systems with a focus on biomimetics: A motion/deformation analysis. *Sustainability* **2024**, *16*, 5697. [CrossRef]
73. Speck, T.; Poppinga, S.; Speck, O.; Tauber, F. Bio-inspired life-like motile materials systems: Changing the boundaries between living and technical systems in the Anthropocene. *Anthr. Rev.* **2022**, *9*, 237–256. [CrossRef]
74. Abouisaadat, A.H. Application of Biomimetic Facades For A More Sustainable Future. *J. Al-Azhar Univ. Eng. Sect.* **2025**, *20*, 1471–1490. [CrossRef]
75. Gardinetti, M. Bosco Verticale de Stefano Boeri: Infraestructura viva y densificación biológica. *Tecnne* **2025**, *30*. [CrossRef]
76. Cocho-Bermejo, A. Adaptive architectural facades: Review 1985–2024. A comparative analysis of Media-TIC, the Arab Institute, and Al Bahar Towers dynamic facades approaches. *Nexus Netw. J.* **2025**, *27*, 925–945. [CrossRef]
77. Giuroiu, A. Al Bahar Towers Responsive Facade/Aedas + Arup. *Architecture Lab, 12 March 2025*. Available online: https://www.architecturelab.net/al-bahar-towers-responsive-facade-aedas (accessed on 23 August 2026).
78. Gilisıralıoğlu, M.K.; Bayraktar, N.T. Thermal Load and Carbon Emissions With Double Façade and BioPCM Configurations in Different Climates. *Energy Storage* **2025**, *7*, e70261. [CrossRef]
79. Rossi, G.D.; Vergani, L.M.; Buccino, F. A Novel Triad of Bio-Inspired Design, Digital Fabrication, and Bio-Derived Materials for Personalised Bone Repair. *Materials* **2024**, *17*, 5305. [CrossRef]
80. Aruta, G.; Ascione, F.; Bianco, N.; Iovane, T.; Mauro, G.M. A responsive double-skin façade for the retrofit of existing buildings: Analysis on an office building in a Mediterranean climate. *Energy Build.* **2023**, *284*, 112850. [CrossRef]
81. Wu, S.; Sun, H.; Duan, M.; Mao, H.; Wu, Y.; Zhao, H.; Lin, B. Applications of thermochromic and electrochromic smart windows: Materials to buildings. *Cell Rep. Phys. Sci.* **2023**, *4*, 101370. [CrossRef]
82. Li, Z.; Zhang, W.; He, B.; Xie, L.; Chen, M.; Li, J.; Zhao, O.; Wu, X. A comprehensive life cycle assessment study of innovative bifacial photovoltaics applied to buildings. *Energy* **2022**, *245*, 123212. [CrossRef]
83. 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. [CrossRef]
84. Kahvecioğlu, B.; Mutlu Avinç, G.; Arslan Selçuk, S. Biomimetic adaptive building façade modelling for sustainable urban freshwater ecosystems: Integration of nature's water-harvesting strategy into sun-breakers. *Biomimetics* **2024**, *9*, 569. [CrossRef]
85. Ullah, A.; Anwar, S.M.; Li, J.; Nadeem, L.; Mahmood, T.; Rehman, A.; Saba, T. Smart cities: The role of Internet of Things and machine learning in realising a data-centric smart environment. *Complex Intell. Syst.* **2024**, *10*, 1607–1637. [CrossRef]
86. Jaffar, H.; Javed, N.; Riaz, A.; Ahmad, H.A.; Iqbal, A.M.; Zhou, C.; Zhang, J. Critical analysis of smart materials in adaptive transparent systems for building façade. *Energy Environ.* **2024**, *37*, 2643–2673. [CrossRef]
87. Kong, X.; Han, Y.; Zhang, X.; Zhao, X.; Yuan, J. Integrated biphasic transparent composite PCM and thermochromic hydrogel smart window: A solution for energy-saving in seasonally temperature-contrasting regions. *Energy Build.* **2025**, *339*, 115773. [CrossRef]
88. Gamage, A.; Upadhyay, A.; Hyde, R. Exploring Bioinspired Climatic Design Strategies for a Low-Carbon Future: A Case Study of a Hot–Humid Climate in Sri Lanka. *Biomimetics* **2025**, *10*, 671. [CrossRef]
89. Koska, A. From Biological Models to Industrial Production: How Industry 4.0 Enables the Man-ufacturability and Scalability of Biomimetic Design. *Biomimetics* **2026**, *11*, 614. [CrossRef]
90. Velliangiri, A. Energy-efficient building design using bio-inspired materials and machine learning optimisation. *J. Smart Infrastruct. Environ. Sustain.* **2025**, *2*, 21–30.
91. Azouz, M.; Elariane, S. Towards energy efficiency: Retrofitting existing office buildings using smart technologies. *J. Eng. Appl. Sci.* **2023**, *70*, 147. [CrossRef]

92. Khan, I.H.; Munawer, T. Vertical Greenery Systems: A Review of Thermal Performance. *Trans. Indian Natl. Acad. Eng.* **2024**, *9*, 25–44. [CrossRef]
93. Long, X.; Jin, Q. Performance evaluation and optimisation of a phase-change material-integrated thermochromic glazing for office buildings. *Indoor Built Environ.* **2026**, *35*, 892–911. [CrossRef]
94. Hilal, N.A.; Haggag, M.; Saleh, A.D. Optimising energy efficiency in high-rise residential buildings in Abu Dhabi's hot climate: Exploring the potential of double skin façades. *Buildings* **2023**, *13*, 2148. [CrossRef]
95. Santamouris, M.; Vasilakopoulou, K. Present and future energy consumption of buildings: Challenges and opportunities towards decarbonisation. *E-Prime–Adv. Electr. Eng. Electron. Energy* **2021**, *1*, 100002. [CrossRef]
96. Saxena, S.; Dixit, F.; Dalapathi, G.K.; Krishna-murthy, S.; Kandasubramanian, B. Bioengineered solar harvesting systems for next-generation applications. *Sol. Energy* **2022**, *231*, 857–879. [CrossRef]
97. Maghrabie, H.M.; Abdelkareem, M.A.; Al-Alami, A.H.; Ramadan, M.; Mushtaha, E.; Wilberforce, T.; Olabi, A.G. State-of-the-art technologies for building-integrated photovoltaic systems. *Buildings* **2021**, *11*, 383. [CrossRef]
98. Olagundoye, O.O.; Bamisile, O.; Ejiyi, C.J.; Bamisile, O.; Ni, T.; Onyango, V. A Review of Artificial Intelligence Techniques for Low-Carbon Energy Integration and Optimization in Smart Grids and Smart Homes. *Processes* **2026**, *14*, 464. [CrossRef]
99. Shao, Y.; Li, J.; Zhou, Z.; Zhang, F.; Cui, Y. The impact of indoor living wall system on air quality: A comparative monitoring test in building corridors. *Sustainability* **2021**, *13*, 7884. [CrossRef]
100. Spaceworx. 2024. Available online: https://spaceworx.com/home/bundle-solutions?countries=SG (accessed on 23 August 2026).
101. Wei, X.; Wang, Y.; Liu, Y.; Ji, K.; Li, K.; Wang, J.; Gu, Z. Biomimetic design strategies for biomedical applications. *Matter* **2024**, *7*, 826–854. [CrossRef]
102. Hu, L.J.; Duan, Z.Z.; Wang, Y.; Ye, W.C.; Che, C.T. Strategies and advances in the biomimetic synthesis of natural products. *Engineering* **2025**, *44*, 30–36. [CrossRef]
103. Usip, E.; Essien, E.; Ema, I. A review of biophilic architectural design strategies and their effects on human wellbeing in contemporary built environments. *Discov. Environ.* **2026**, *4*, 170. [CrossRef]
104. Xiao, C.; Seong, D. Research on the application of biomimetic design in art and design. *Biomimetics* **2025**, *10*, 541. [CrossRef]
105. Abedanzadeh, S.; Nourisefat, M.; Moosa-vi-Movahedi, Z. Bioinspiration and biomimicry in lifestyle. In *Rationality and Scientific life-Style for Health*; University of Tehran Science and Humanities Series; Springer: Berlin/Heidelberg, Germany, 2021. [CrossRef]
106. Vanian, V.; Fanaradelli, T.; Rousakis, T. A Comprehensive Review of Vertical Forest Buildings: Integrating Structural, Energy, Forestry, and Occupant Comfort Aspects in Renovation Modelling. *Fibres* **2025**, *13*, 101. [CrossRef]
107. Ali, M.M.; Al-Kodmany, K.; Armstrong, P.J. Energy efficiency of tall buildings: A global snapshot of innovative design. *Energies* **2023**, *16*, 2063. [CrossRef]
108. Bonomo, P.; Frontini, F.; Loonen, R.; Reinders, A. Comprehensive review and state of play in the use of photovoltaics in buildings. *Energy Build.* **2024**, *323*. [CrossRef]
109. Gönül, H. The building edge as public space: Discussing the contemporary design approach with five projects from Copenhagen. *Kent. Akad.* **2022**, *15*, 798–818. [CrossRef]
110. Ribeiro, A.S. Biomimicry Technology. 2024. Available online: https://heatele101.wixsite.com/projetoheat/post/re-su-mo-engenharia-e-toxicologia-dra-adriana-schalkwijk-ribeiro (accessed on 23 August 2026).
111. Doncaster, C.P.; Bullock, J.M. Living in harmony with nature is achievable only as a non-ideal vision. *Environ. Sci. Policy* **2024**, *152*, 103658. [CrossRef]
112. Genet, K.O. Living Architecture: Buildings as a Regenerative Part of Their Ecosystems. Master's Thesis, Unitec, Te Pūkenga—New Zealand Institute of Skills and Technology, Auckland, New Zealand, 2023.
113. Park, W.Y.; Shah, N. Enhancing the Energy Efficiency of Room Air Conditioners in Malaysia: Opportunities and Impact Analysis. 2025. Available online: https://escholarship.org/uc/item/75h9f0xc (accessed on 23 August 2026).
114. Ratchawang, S.; Chotpantarat, S.; Chokchai, S.; Takashima, I.; Uchida, Y.; Charusiri, P. A review of ground source heat pump application for space cooling in Southeast Asia. *Energies* **2022**, *15*, 4992. [CrossRef]
115. Jon, C.K.; Islam, M.R.; Choon, N.K.; Shah-zad, M.W. *Advances in Air Conditioning Technologies: Improving Energy Efficiency*; Springer Nature: Singapore, 2020. Available online: https://link.springer.com/book/10.1007/978-981-15-8477-0 (accessed on 23 August 2026).
116. Kauffman, C.M.; Martin, P.L. *The Politics of Rights of Nature: Strategies for Building a More Sustainable Future*; MIT Press: Cambridge, MA, USA, 2021; 290p. [CrossRef]

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