Lawrence Berkeley National Laboratory
LBL Publications

Title
Nature as architect: Global performance evidence for building biomimetics across climates

Permalink
https://escholarship.org/uc/item/8km3p865

Journal
Nexus, 3(4)

ISSN
1900-9909

Authors
Shi, Chenxi
Hao, Siyuan
Hong, Tianzhen
et al.

Publication Date
2026-12-01

DOI
10.1016/j.ynexs.2026.100173

Copyright Information
This work is made available under the terms of a Creative Commons Attribution License, available at https://creativecommons.org/licenses/by/4.0/

Peer reviewed

eScholarship.org Powered by the California Digital Library
University of California

Nexus
Review

Nature as architect: Global performance evidence for building biomimetics across climates

Chenxi Shi,[1] Siyuan Hao,[1] Tianzhen Hong,[2] Qinhui Lu,[3] Jiyuan Wu,[1] Zhe Wang,[3] Fengmin Su,[1] Wei Wang,[1,*] Xiangfeng Li,[1,*] and Yang Zhou[4,*]

[1]School of Architecture, Southeast University, Nanjing, Jiangsu Province 210096, China
[2]Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[3]The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong SAR 999077, China
[4]School of Materials Science and Engineering, Southeast University, Nanjing, Jiangsu Province 210096, China
*Correspondence: weiwang@seu.edu.cn (W.W.); archli@vip.163.com (X.L.); tomaszy@seu.edu.cn (Y.Z.)
https://doi.org/10.1016/j.ynexs.2026.100173

BROADER CONTEXT

Growing climate and resource pressures are driving greater demands on buildings. Biomimetics addresses these needs by translating how organisms resist loads and regulate their surroundings into building configurations, materials, and devices. However, fragmented evidence makes it difficult to evaluate the effectiveness of building biomimetic strategies and apply them appropriately.

This review synthesized nearly a decade of research on performance-oriented building biomimetics. By integrating evidence on structural safety, occupant comfort, and energy efficiency across application hierarchies and climate zones, this study connected biological principles to performance effects and identified pathways, advantages, and gaps. The framework supports strategy selection, guides the systematic development of building biomimetics, and strengthens validation in complete buildings. These insights facilitate the translation of biomimetics into high-performance buildings and sustainable cities.

ABSTRACT

Biomimetic strategies offer diverse pathways to improve building performance. Nevertheless, their performance effects across climates and application hierarchies remain poorly understood. This systematic review and meta-analysis synthesized qualitative and quantitative evidence from 185 peer-reviewed studies. Research entries are concentrated in temperate climate zones (59.6%) and material hierarchy (62.2%). These concentrations are particularly pronounced in structural safety, where studies focus on strength and toughness. The mean improvements in these indicators are 145.6% and 875.6%, respectively. Research priorities for occupant comfort vary with climatic contexts and occupant requirements, while heterogeneous indicators limit performance comparisons. For energy efficiency, material strategies achieve mean reductions of 34.0% in cooling load and 29.5% in total load, while configurations show considerable energy-saving potential. Daytime cooling varies across climate zones, with a mean reduction of $9.29^{\circ}C \pm 4.16^{\circ}C$ in temperate climates, which provide the largest evidence base. These findings show that climate zones and application hierarchies are associated with differences in the performance effects of building biomimetic strategies. This study provides an evidence-based knowledge map for selecting biomimetic strategies across project contexts and identifies critical gaps and development priorities. It also supports the translation of biomimetic knowledge through research and technology development into building practice, contributing to more sustainable and resilient buildings.

INTRODUCTION

Buildings are increasingly expected to meet multiple performance demands under growing climate, environmental, and resource pressures. Among these objectives, structural safety, occupant comfort, and energy efficiency are particularly important because they determine the ability of buildings to remain safe, habitable, and resource efficient under changing conditions. Structural safety provides the basis for reliable building operation, occupant comfort determines the quality of the indoor environment, and energy efficiency has become increasingly important as buildings seek to maintain required environmental conditions with lower resource consumption. Improving performance across these three dimensions is a major challenge for establishing sustainable buildings and cities.

Biomimetics provides a promising approach by abstracting functional principles from biological systems and translating them into engineering solutions. In buildings, biological morphology, microstructure, and adaptive mechanisms have inspired responsive envelopes, high-performance materials, energy-regulating components, and other performance-oriented technologies. Spontaneous biological responses have been translated into biomimetic adaptive building skins (Bio-ABSs) that respond to environmental stimuli.[1] López et al. expanded the repertoire of environmentally adaptive strategies for building skins by drawing on plant mechanisms, including light reflection, water utilization, and touch sensing.[2] The hierarchical microstructure of nacre has continued to inspire materials with enhanced mechanical properties and damage tolerance.[3,4] Meanwhile, rapid advances in observational technologies enhance understanding of biological principles,[5] and high-performance computational simulations enable multi-objective optimization across complex design spaces.[6] As a result, the range of biological prototypes explored in architecture has consistently expanded, encompassing organisms from diverse habitats and elevations (Figure S1). Building biomimetics has developed into a highly interdisciplinary field spanning architecture, structural engineering, materials science, and building environmental research.

Despite rapid advances in building biomimetics and its demonstrated potential to enhance building performance, existing studies have largely focused on isolated components or individual performance indicators, with limited attention to cross-hierarchy integration.[7] Current reviews tend to catalog technical cases, emphasizing the exploration of biomimetic strategies, whereas quantitative evidence on whether reported benefits remain consistent across application hierarchies and climate zones is particularly limited.[8,9] Consequently, the factors shaping performance differences and the mechanisms underlying their effectiveness remain insufficiently understood.[10,11] This limits evidence-based selection of biomimetic strategies and constrains their translation from individual demonstrations to broader building applications.

© 2026 The Authors. Published by Elsevier Inc. on behalf of The Hong Kong Polytechnic University.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

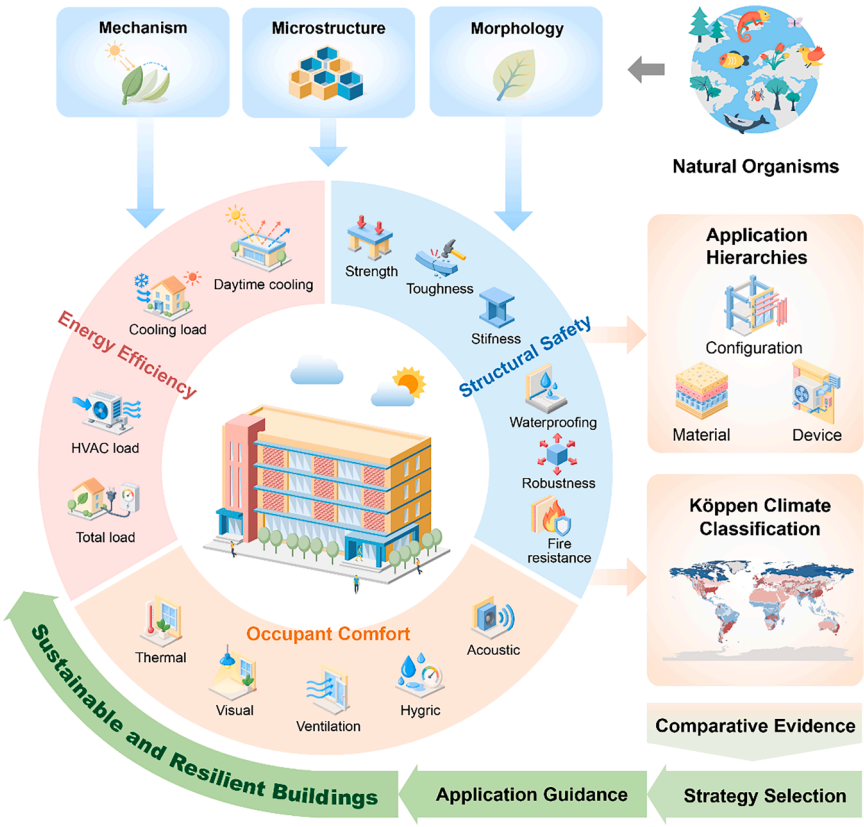


Figure 1. Research framework for performance-oriented building biomimetics

By integrating global research patterns with quantitative and qualitative performance evidence, this study establishes a systematic framework that traces the pathway from biological inspiration through building applications to performance objectives and synthesizes the evidence across application hierarchies and Köppen-Geiger climate zones (Figure 1). The framework enables comparative evaluation, strategy selection, and application guidance, supporting more sustainable and environmentally responsible building design.

GLOBAL RESEARCH LANDSCAPE OF PERFORMANCE-ORIENTED BUILDING BIOMIMETICS

The global distribution of performance-oriented building biomimetics is markedly uneven across climate zones (Figure 2A). Among the 18 Köppen-Geiger climate zones represented in the reviewed literature (Figure 2B), about 60% of climate-zone entries fall within temperate climates (C-type), particularly in humid subtropical (Cfa) and oceanic (Cfb) climates. By contrast, research in tropical (A-type; 4.9%) and polar (E-type; 0.5%) climate zones remains particularly scarce. The reviewed studies show a marked geographic concentration, with limited coverage of climate zones facing substantial climate challenges.

A similar concentration is evident across application hierarchies (Figure 2C). Material-related strategies account for 62.2% of the reviewed studies and constitute the dominant research pathway, particularly for building structural safety. Their prevalence is associated with controllable experimental conditions and established validation pathways. Building configurations are more prominent in studies of occupant comfort and environmental regulation, while device-related applications remain comparatively limited. Publication activity increased steadily over most of the review period, accompanied by growing attention to energy efficiency (Figure 2D). The apparent decline observed in 2025 may be partly due to the literature search ending on October 1, 2025.

BIOMIMETIC ENHANCEMENT OF STRUCTURAL SAFETY

Structural safety, as a foundation of building performance, has long been a major concern. As shown in Figure 3A, 84.5% of the studies focus on the material hierarchy, mainly involving composites, porous lightweight materials, and surface materials. These strategies enhance mechanical performance by emulating the microstructures, hierarchical organizations, and biomineralization processes of biological hard tissues, such as coelacanth scales and the dactyl clubs of mantis shrimp.[15] Studies on building configurations and devices remain limited and typically draw on biological morphologies, such as eggshell curvature and avian load-bearing configurations, to improve overall load-bearing capacity and damage resistance.[16,17] This uneven distribution limits quantitative comparisons across application hierarchies. Evidence for configurations and devices is insufficient to support subgroup analysis. The distribution of reported structural safety indicators is also uneven (Figure 3B). Strength (43.2%) and toughness (30.5%) were the dominant indicators. Across the reported effect values, biomimetic strategies yielded mean improvements of 145.6% in strength and 875.6% in toughness. These

To examine how reported performance varies across technical and environmental conditions, this study organizes the existing evidence along two complementary dimensions: application hierarchy and climate zone. Based on how biological principles are implemented in buildings, biomimetic applications are classified into building configuration, material, and device. Strategies based on configurations translate biological morphology, structural organization, or adaptive mechanisms into architectural forms and envelope systems, as exemplified by leaf-inspired adaptive photovoltaic louvers.[12] Material-related strategies primarily reproduce biological microstructures and hierarchical organizations to modify intrinsic material properties; gradient structures found in bone, shells, and bamboo, for example, have inspired lightweight, high-strength composites.[13] Device-related strategies incorporate biological principles into building-integrated components and operational systems, such as solar façades inspired by leaf venation.[14] In parallel, the reviewed studies are assigned to Köppen-Geiger climate zones based on reported climatic conditions or the geographic background of the research, allowing their geographic distribution and reported performance to be analyzed across climate zones. By combining these two dimensions, the study examines how biomimetic strategies applied at different building hierarchies perform across climate contexts in relation to structural safety, occupant comfort, and energy efficiency.

On this basis, the study analyzed 185 peer-reviewed studies on performance-oriented building biomimetics across three application hierarchies and 18 Köppen-Geiger climate zones to address three research questions.

(1) What are the distribution patterns of performance-oriented building biomimetics across Köppen-Geiger climate zones and application hierarchies?
(2) How do the performance effects of biomimetic strategies differ across climate zones and application hierarchies for different performance objectives?
(3) How can suitable research pathways and biomimetic strategies be selected for different application contexts?

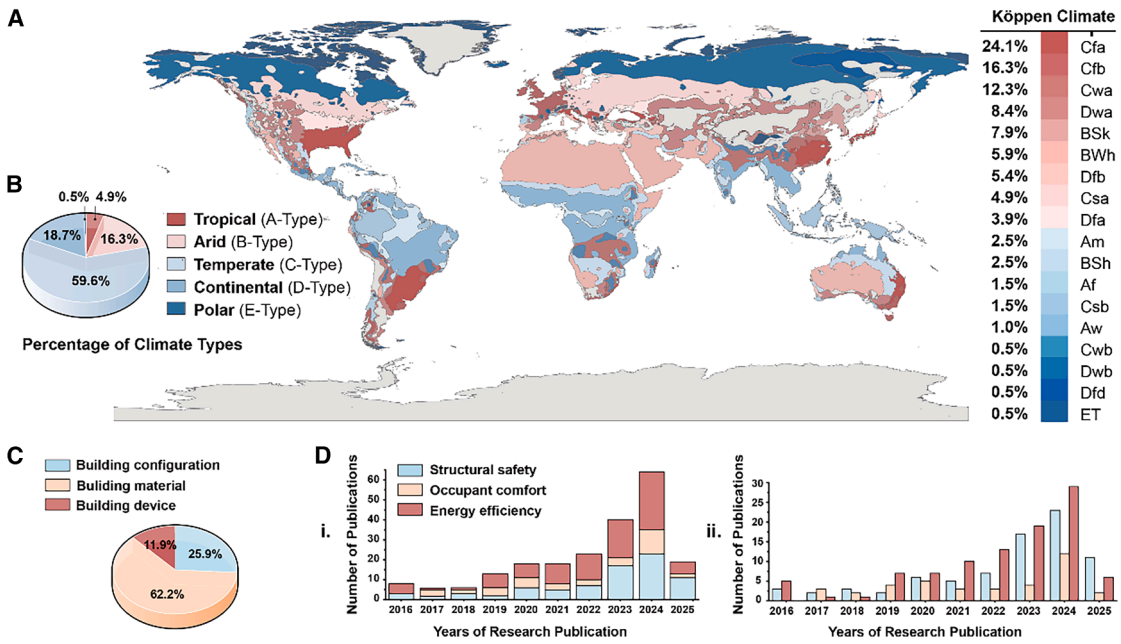


Figure 2. Global evidence map and systematic analysis of building biomimetics

(A) Geographic distribution of the reviewed studies by Köppen-Geiger climate zone.

(B) The distribution across climate zones.

(C) The distribution across application hierarchies.

(D) The distribution of publications under different performance objectives, shown as stacked (i) and grouped (ii) bar charts.

gains were achieved by optimizing material microstructures, drawing on biological prototypes such as the hierarchical organization of bird nests and the gradient structures of diatoms.[18,19] Stiffness (8.5%), which characterizes resistance to deformation, is primarily investigated through modifications to material properties.[20] Robustness (7.6%) characterizes the capacity of structures to maintain performance under damage and extreme actions. Accordingly, Nie et al. translated DNA-inspired structural configurations into a high-rise building and reduced inter-story drift ratios by 16.54%–59.20%.[22] In addition, specialized safety indicators, such as waterproofing and fire resistance, have demonstrated substantial gains through biomimetic strategies. Surface structures inspired by the lotus leaf significantly improve hydrophobicity, achieving water contact angles exceeding 167°.[24] Biomimetic replication of aquatic plant structures, such as taro stems and kelp, has increased the limiting oxygen index (LOI) of the tested materials to above 24.5%, indicating highly efficient flame retardancy in building envelope systems.[21,25]

From a climate perspective (Figure 3E), structural-safety studies are concentrated mainly in temperate climates, with Cfa alone accounting for 27.7% of the evidence, including Sydney, Hong Kong, and Nanjing. In contrast, studies are underrepresented in A-type, and none were identified in E-type. The structural-safety indicators investigated also vary across climate zones (Figure 3F). Among the limited studies conducted in A-type, robustness is the most frequently represented indicator. Studies in arid climates (B-type) cover a more balanced range, with greater attention to water-related performance. Fire resistance is more frequently investigated in C-type and cold climates (D-type). The comparatively large evidence base for strength (Figure 3G) and toughness (Figure 3H) supported meta-analyses across climate zones. Numbers in parentheses indicate the contributing effect entries. Biomimetic strategies in C-type have the largest evidence base, primarily from material studies, with mean increases of 110.7% ± 41.9% in strength and 708.0% ± 444.8% in toughness. Studies in B-type report lower mean improvements in strength (48.6% ± 12.1%) and toughness (72.2% ± 38.1%). Compared with C-type, D-type shows a similar mean strength gain (102.9% ± 72.1%) but a larger and less precisely estimated mean toughness improvement (2516.6% ± 2698.7%).

BIOMIMETIC REGULATION OF OCCUPANT COMFORT

As societies develop and living standards rise, expectations for occupant comfort in the built environment continue to increase. Biomimetics offers a relevant approach because organisms achieve environmental adaptation with limited resource and energy inputs.[26] To examine how this principle is translated into building applications, the reviewed studies were classified by the primary environmental factor regulated, yielding five recurring aspects of occupant comfort: thermal comfort, visual comfort, hygric comfort, ventilation organization, and acoustic comfort. Given the substantial heterogeneity in performance indicators across studies, evidence in this domain was synthesized qualitatively. As illustrated in Figure 4A, although each responds to a different environmental factor, most biomimetic strategies act through the building envelope, where heat, light, moisture, airflow, and sound are regulated between indoor and outdoor environments. Strategies for thermal comfort primarily address heat transfer and dissipation, often drawing on thermoregulatory adaptations of organisms in extreme climates. For example, the microscale wrinkled structure of African elephant skin has been emulated to enhance moisture retention and evaporative cooling, improving indoor thermal conditions and reducing cooling loads.[32] Visual comfort depends on regulating daylight penetration and distribution. Dynamic façades inspired by photosensitive plants can translate responsive movement into shading regulation to balance daylighting and energy use.[33] Humidity-responsive seed capsules have informed moisture-actuated envelope systems,[34] and the touch-responsive movement of *Mimosa pudica* has inspired adaptive components for ventilation control.[27] Acoustic comfort research focuses on biological surface structures that reduce airflow-induced noise at building surfaces.[28]

The distribution of studies varies markedly across comfort categories, as shown in Figure 4B. Thermal and visual comfort dominate, most likely reflecting their direct influence on indoor environmental quality and occupant experience. Hygric and ventilation-related studies follow, while acoustic comfort remains relatively underexplored. Building configurations account for the largest share in most comfort categories. These strategies directly mediate indoor-outdoor environmental exchange through building form and envelope design.

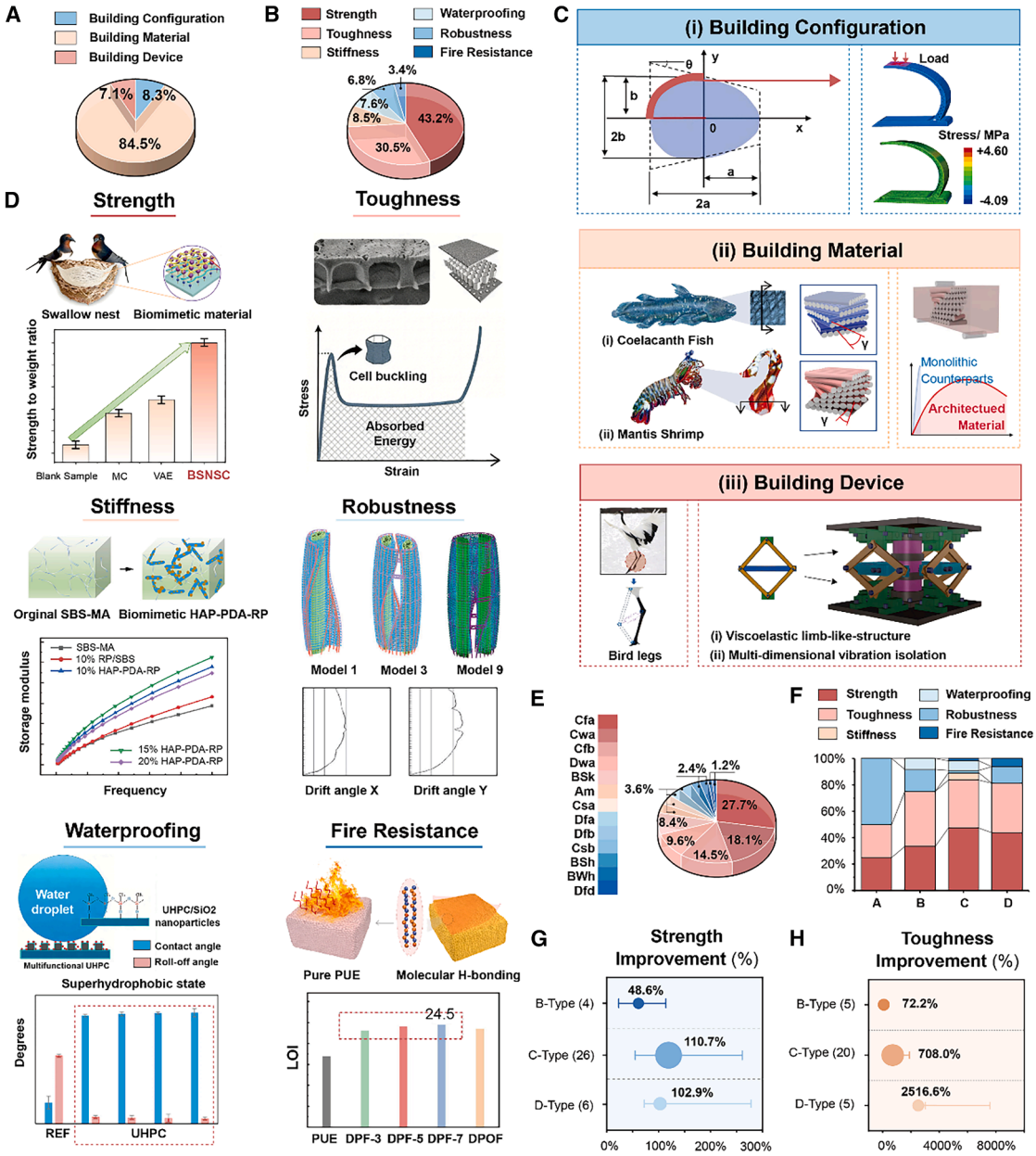


Figure 3. Biomimetic strategies for structural safety across hierarchies, indicators, and climate zones

(A) Distribution of studies across application hierarchies.

(B) Distribution of reported structural safety indicators.

(C) Representative biomimetic applications across hierarchies. Adapted from Prihar et al.,[15] published under a CC BY license, and He et al.[16] and Dong et al.,[17] with permission from Elsevier.

(D) Biomimetic approaches and reported improvements in selected performance indicators. Adapted from Zheng et al.[18] and Musenich et al.,[19] with permission from American Chemical Society; Li et al.[20] and He et al.,[21] with permission from Elsevier; Nie et al.,[22] with permission from John Wiley & Sons; and Mumtaz et al.,[23] published under a CC BY license.

(E) Geographical distribution of studies across climate zones.

(F) Relative distribution of performance indicators across climate zones.

(G) Forest plot of strength improvements across climate zones. Points indicate mean effects, and horizontal error bars represent 95% confidence intervals.

(H) Forest plot of toughness improvements across climate zones. Points indicate mean effects, and horizontal error bars represent 95% confidence intervals.

Materials and devices receive comparatively less attention. Climate shapes the comfort functions addressed by biomimetic research (Figure 4C). C-type exhibits the highest research concentration, especially in studies addressing thermal, hygric, and visual comfort. These studies frequently focus on organisms with high environmental sensitivity and adaptive behavior. Studies in B-type place greater emphasis on thermal comfort and ventilation, frequently drawing inspiration from the forms and regulatory mechanisms of heat- and drought-adapted organisms, such as cacti.[35,36] Research in A-type is more concentrated on thermal comfort and ventilation, particularly in tropical monsoon (Am) and tropical savanna (Aw) climates.

BIOMIMETIC OPTIMIZATION OF BUILDING ENERGY EFFICIENCY

Climate change, mounting energy pressures, and rising living standards have made energy efficiency a core requirement in contemporary buildings. Building energy performance depends on the regulation of

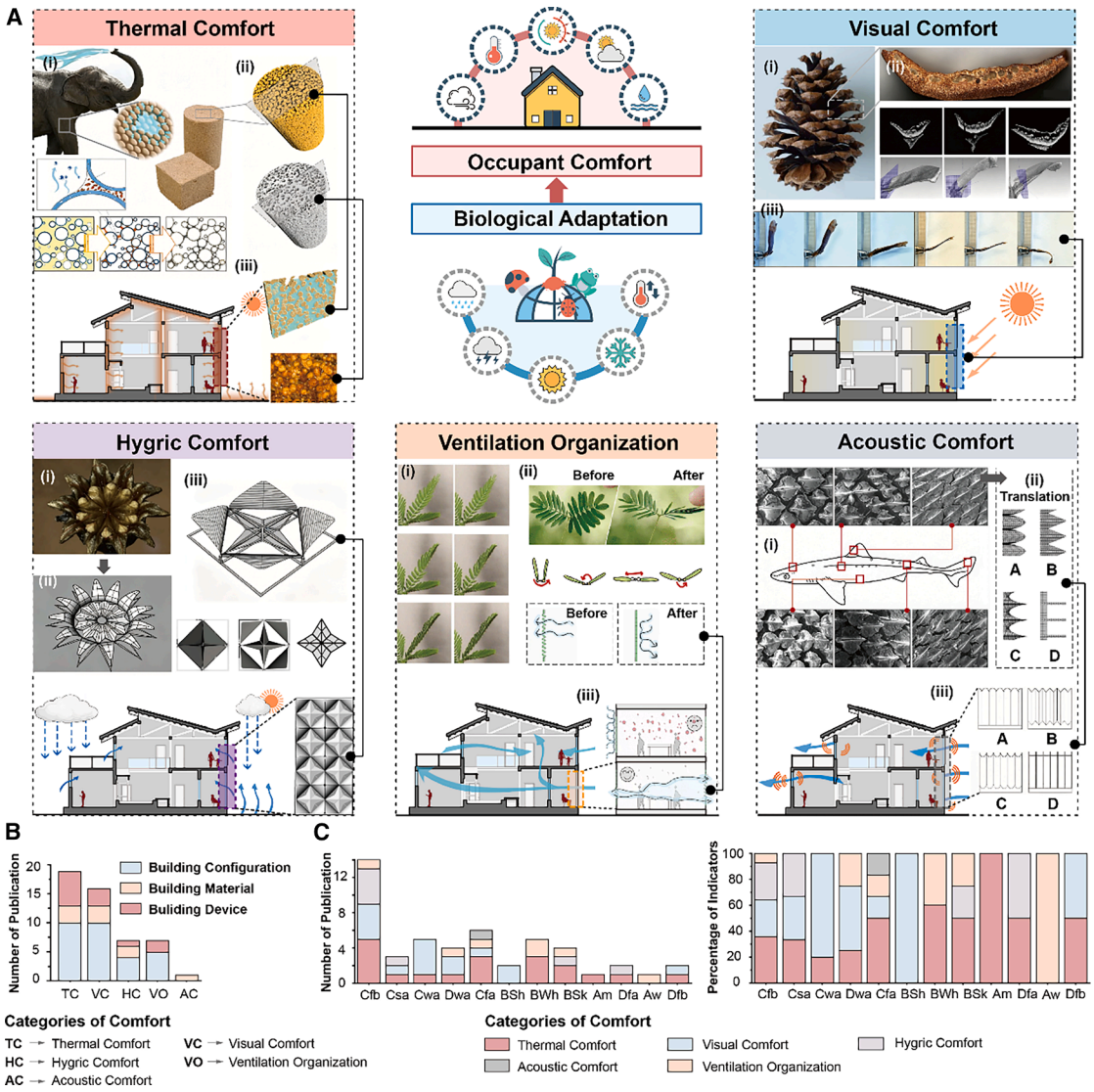


Figure 4. Building biomimetics for occupant comfort

(A) Biological models and representative biomimetic applications for occupant comfort. Adapted from Sankaewthong et al.,[27] Wang et al.,[28] and Ulrich et al.,[29] published under a CC BY license, and He et al.[30] and Khosromanesh and Asefi,[31] with permission from Elsevier.

(B) Distribution of studies across comfort categories and application hierarchies.

(C) Distribution of studies across climate zones and relative proportions of comfort-oriented studies.

energy exchange and use while maintaining suitable indoor conditions. Biological systems manage heat and energy through passive adaptation and efficient resource use, providing useful models. In related research, these models are translated into configurations, materials, and devices that regulate different stages of energy transfer, storage, and use.

The three application hierarchies show distinct roles in this process (Figure 5A). Building configurations account for approximately 33.0% of the studies and mainly regulate the exchange of solar radiation, airflow, and heat through the building envelope. Responsive façades can alter their geometry or opening state with environmental changes, thereby coordinating daylight, solar gain, and thermal conditions.[6,40] Sommese et al. emulated the movement mechanism of the *Gazania* flower to design a light-responsive dynamic façade that adjusts shading without additional actuation energy, improving daylight use and building energy performance.[37] Material-related research (52.8%) constitutes the core of this field and addresses multiple processes of heat and energy transfer. The material categories, biomimetic principles, all reported performance data, application contexts, and evidence limitations are summarized in Table S3. Chameleon- and squid-inspired electrochromic and thermochromic materials regulate solar transmission and heat gain through adaptive optical responses.[41–43] Okra-inspired composite phase-change materials use their internal structure to improve heat transfer and thermal storage.[44] Multilayered and porous structures found in biological skins and tissues have inspired aerogels and insulation materials with low thermal conductivity, helping limit heat transfer through the building envelope.[45,46] With the intensification of global warming, biomimetic materials for radiative cooling have emerged as a prominent research focus. Radiative-cooling films and glass use biological surface and optical structures to enhance solar reflection and thermal emission.[47–49] Zhang et al. developed a low-cost biomimetic radiative cooling glass (Bio-RC glass) inspired by beetle exoskeletons, achieving daytime cooling of up to 18.1°C and energy savings of 23.4% while maintaining high transmittance.[50] Biomimetic materials further extend to energy conversion. A fly ash nanocomposite material inspired by the microstructural organization of broccoli demonstrates integrated photothermal conversion and thermal storage.[38] Wang et al. further emulated the xylem ray structure of plant stems to

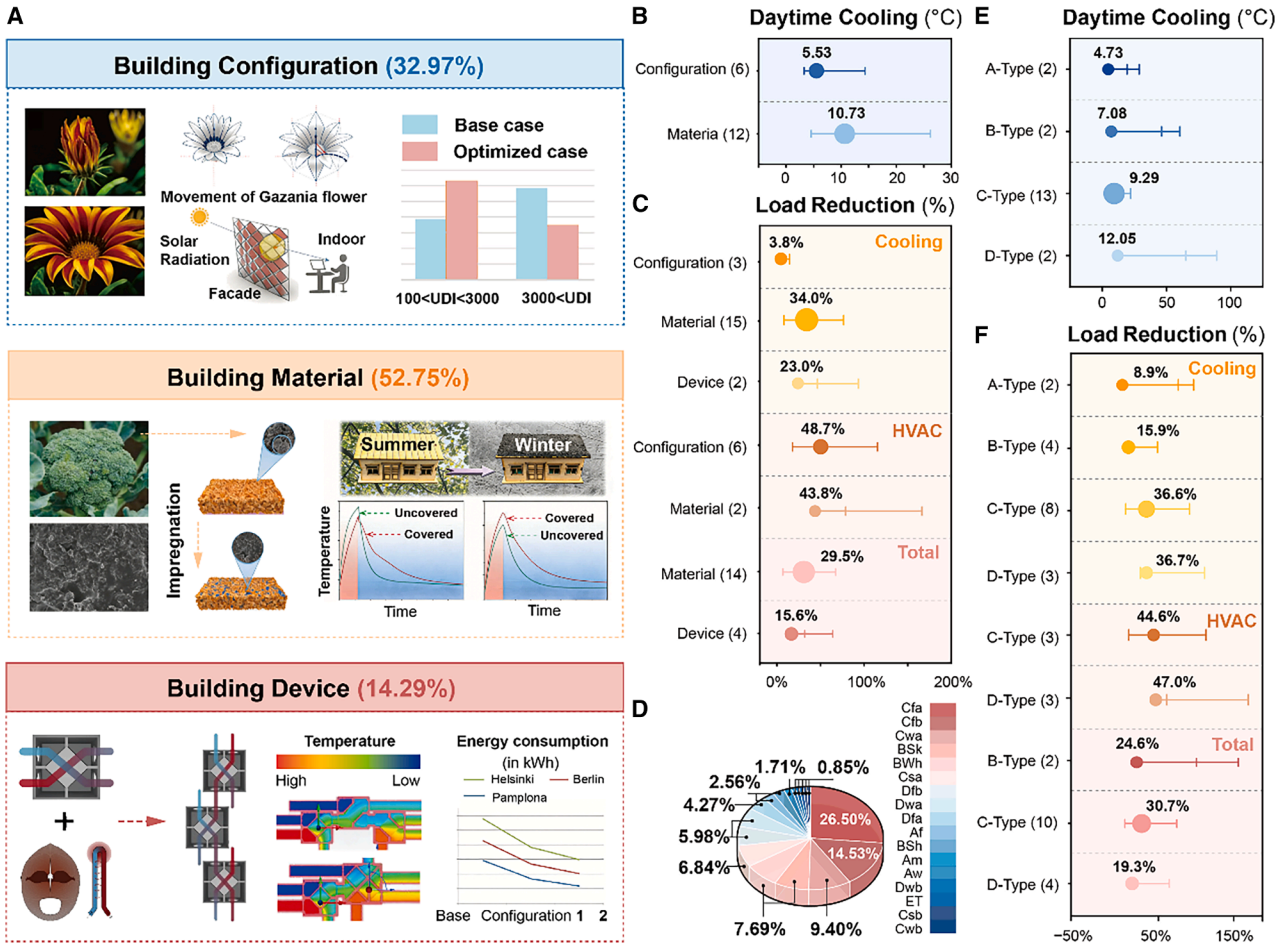


Figure 5. Biomimetic applications for building energy efficiency: Distribution and performance across application hierarchies and climate zones

(A) Overview of distribution, representative studies, and reported performance across application hierarchies. Adapted from Sommese et al.,[37] published under a CC BY license, and Jiang et al.[38] and Bermejo-Busto et al.,[39] with permission from Elsevier.

(B) Forest plot of daytime cooling effect across application hierarchies. Points indicate mean effects, and horizontal error bars represent 95% confidence intervals.

(C) Forest plot of energy-saving effects across application hierarchies. Points indicate mean effects, and horizontal error bars represent 95% confidence intervals.

(D) The distribution across climate zones.

(E) Forest plot of the daytime cooling effect of biomimetic technology across climate zones. Points indicate mean effects, and horizontal error bars represent 95% confidence intervals.

(F) Forest plot of cooling-load, HVAC-load, and total-load reductions across climate zones. Points indicate mean effects, and horizontal error bars represent 95% confidence intervals.

endow cement-based composites with thermoelectric properties, enabling building-integrated energy generation.[51] Research on building devices (14.3%) remains comparatively limited. These devices often translate biological regulatory and survival mechanisms into building systems for heat and energy management. For example, heat-recovery systems inspired by the tuna rete mirabile have reported energy savings of up to 44.5%.[39]

Given the substantial variation in energy-saving pathways and performance indicators across studies, the quantitative synthesis was restricted to outcomes reported with sufficient frequency and consistency: daytime cooling (°C) and reductions (%) in cooling, heating, ventilation, and air-conditioning (HVAC), and total loads. As shown in Figure 5B, studies on materials (10.73°C ± 4.62°C) report a higher mean daytime cooling effect than those on configurations (5.53°C ± 3.27°C). Load reductions also varied across application hierarchies. Material strategies achieve mean reductions of 34.0% ± 9.0% in cooling load and 29.5% ± 6.3% in total load (Figure 5C), while the mean HVAC-load reduction (43.8% ± 78.8%) is less precisely estimated than that for building configurations (48.7% ± 16.4%). Research on building devices remains limited, with mean reductions of 23.0% ± 44.5% in cooling load and 15.6% ± 30.7% in total load.

Climate shapes these energy effects because external temperature, solar radiation, and moisture directly affect building heat exchange (Figure 5D). Studies are predominantly concentrated in C-type, particularly in Cfa (26.5%) and Cfb (14.5%) climates, while other climate types remain underrepresented. Notably, E-type was represented only in energy-efficiency research. The climate influence is particularly evident in daytime cooling. As shown in Figure 5E, research in C-type reports a mean daytime cooling of 9.29°C ± 4.16°C, with a maximum reported roof-surface temperature reduction of 25°C. In contrast, research in D-type has a less precise mean estimate (12.05°C ± 76.89°C), largely due to the limited sample size. Figure 5F shows energy-saving performance across climate zones. Research in C-type contributes the largest number of effect entries for cooling-load and total-load reductions, achieving mean reductions of 36.6% ± 16.3% (maximum: 74.4%) and 30.7% ± 10.2% (maximum: 48.7%), respectively. Other climate types have fewer contributing entries and less precise mean estimates. A-type includes only two effect entries for cooling-load reduction, showing a mean cooling-load reduction of 8.9% ± 70.9%.

The corresponding effects are larger in B-type (15.9% ± 18.4%) and D-type (36.7% ± 40.5%). Evidence on HVAC-load reduction is sparse, with one study each in A-type and B-type and three effect entries each in C-type (44.6% ± 15.8%) and D-type (47.0% ± 57.3%), with particularly wide uncertainty in the latter. Studies on total-load reduction are concentrated in C-type. The sole study in A-type reports a reduction of approximately 22.4%,[52] and the mean reductions in B-type (24.6% ± 98.5%) and D-type (19.3% ± 25.0%) also exhibit substantial uncertainty.

DISCUSSION

This study synthesized nearly a decade of building biomimetics research, organized around structural safety, occupant comfort, and energy efficiency. For these performance objectives, biomimetic strategies exhibit distinct advantages and mechanisms across application hierarchies and climate zones.

Material applications accounted for the largest share of the reviewed studies (62.2%), consistent with previous reviews.[26] This pattern may reflect their high experimental controllability and established quantitative indicators. Across climate zones, 59.6% of evidence entries came from C-type. This concentration may reflect both building-performance demands and regional research capacity: seasonal environmental variation creates substantial needs for indoor environmental regulation and energy optimization, while dense urban building stocks, economic development, and established research infrastructure support sustained technological investigation. These concentrations were particularly pronounced in structural safety, where material applications accounted for 84.5%. Within C-type, biomimetic strategies achieved improvements of 110.7% ± 41.9% in strength and 708.0% ± 444.8% in toughness. For occupant comfort, biomimetic strategies were applied to regulate thermal, visual, hygric, ventilation, and acoustic conditions. Building configurations play a prominent role by directly mediating indoor-outdoor environmental exchange through envelope forms. Research priorities vary with climatic stresses and indoor environmental requirements. Studies in C-type address a broader range of comfort objectives, whereas those in A-type and B-type focus on thermal comfort and ventilation. As a core focus of building biomimetics, energy efficiency shows clear performance disparities across application hierarchies. Through internal structures and surface properties, biomimetic materials provide continuous regulation of heat transfer, storage, and radiation, achieving mean reductions of 34.0% ± 9.0% in cooling load and 29.5% ± 6.3% in total load. Building configurations act directly by modifying form and thermal interactions, showing a higher mean HVAC-load reduction in the reviewed studies. Across the three performance objectives, climate zones provide the environmental context for biological model selection, shape performance objectives, and contribute to differences in reported performance.[53,54] Application hierarchies define the point and scale of intervention. Together, they shape the implementation pathways and performance effects of building biomimetic strategies.

To ensure the reliability and traceability of the evidence base, this study was restricted to peer-reviewed studies with accessible full texts. This criterion may limit the coverage of technical reports, demonstration projects, and regional implementation experience. For studies without an explicit climate context, the institutional location of the first author was used as a proxy for the geographic background of the research. Most proxy-classified studies addressed structural safety (Table S4), consistent with the prevalence of laboratory-based material testing in this domain. Excluding proxy-classified entries had little effect on the distribution across major climate types, supporting the robustness of the geographic research pattern (Table S5). Subgroup effects were interpreted in relation to the available evidence, with greater caution for groups containing fewer contributing entries. Differences in experimental scale, baseline conditions, model settings, and evaluation methods further complicate the interpretation of synthesized effects. Therefore, for subgroups with limited samples or high heterogeneity, the reported effects were interpreted primarily as the performance potential of biomimetic strategies under the corresponding conditions. Table S15 summarizes the main sources of uncertainty, their underlying causes, and their potential implications for the synthesized evidence.

Further development of building biomimetics requires broader climate coverage, a unified performance evaluation framework, integrated optimization of building performance, and overall engineering verification. First, the evidence base is concentrated in temperate climates, with limited coverage of tropical, arid, and polar climates. Research in these underrepresented contexts must address demanding environmental conditions and potential constraints on energy availability. Filling this research gap will help unlock the full performance potential of building biomimetics and expand the evidence base for technology selection. Second, the interdisciplinary field of building biomimetics demands unified performance measurement, baseline definitions, and evaluation methods to improve cross-disciplinary comparability and reliability of studies. Third, further research should integrate multiple performance objectives to meet growing demands for building resilience and long-term sustainability. Finally, practical implementation requires whole-building validation. Building projects must account for safety requirements, coordination among building systems, and substantial capital investment. Moving from evidence at individual application hierarchies to whole-building validation requires evaluating the conditions for mass manufacturing and installation, integration with existing building systems, and maintenance at an acceptable cost. The extent to which performance benefits are retained under these practical constraints should be assessed at building scale. Biomimetic technologies require performance validation throughout their life cycle to establish their long-term stability and suitability for building applications.

CONCLUSION

Drawing on 185 studies published over nearly a decade, this study establishes an integrated evidence framework combining qualitative and quantitative analyses. It characterizes building biomimetics across application hierarchies and climate zones in relation to three core performance objectives: structural safety, occupant comfort, and energy efficiency. Structural safety shows substantial reported relative improvements in strength and toughness. Material strategies draw on biological microstructures or material-formation processes to enhance intrinsic properties and account for the largest share of the reviewed studies (62.2%). Building configurations enable more direct regulation of performance at the building scale, achieving a mean reduction of 48.7% in heating, ventilation, and air-conditioning loads. Climate zones not only shape local performance priorities but also influence the selection of biological models and the reported performance of biomimetic solutions.

By linking biological principles to quantified performance patterns across application hierarchies and climate zones, the framework supports the evaluation and selection of biomimetic strategies during building planning and design. Meanwhile, this work identifies existing research gaps and inherent limitations in climate coverage, performance evaluation, and whole-building validation, helping define priorities for future research and development. These findings advance the systematic development of building biomimetics and contribute to delivering safe, adaptable, and resource-efficient buildings for sustainable urban development.

METHODS

Literature searches and synthesis

To ensure the transparency and reproducibility of the research process, this study adheres to the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines for conducting the systematic review. The literature screening workflow is presented in Figure S2. Literature searches were conducted across three major databases, including Web of Science, Scopus, and PubMed, covering publications from January 1, 2016, to October 1, 2025. The search strategies were developed from the keyword combinations summarized in Table S14. Only peer-reviewed studies were included, with no language restrictions. This review included direct building biomimetics, defined as research explicitly developed for

buildings or their constituent parts. Research originally developed for other fields and subsequently transferred or adapted to building applications was classified as indirect building biomimetics and excluded from this review. The development of indirect building biomimetics and its influence on the field are discussed in Note S1.

The systematic review was conducted in three stages: (1) data collection, in which studies employing biomimetic approaches to address building performance were identified using predefined search terms. (2) Categorization, in which studies were classified according to performance objectives, application hierarchies, and Köppen-Geiger climate zones. Climate zones were assigned from reported research, experimental, or simulation contexts where available; otherwise, the first author's institutional location was used as a proxy for research background, as detailed in Methods S1. (3) Data extraction, in which relevant quantitative indicators and associated data were extracted for each performance category. A total of 185 studies formed the evidence base for the systematic review and subsequent quantitative synthesis.

Classification and definition of building performance

Building performance is widely recognized as a multidimensional construct. International standards and major green building assessment systems, including ISO 19208, LEED (v.5 Building Design and Construction), and BREEAM, consistently address three fundamental requirements.[55] Accordingly, this study organizes building performance into three core dimensions: (1) structural safety concerns the ability of buildings and components to maintain reliable performance under external actions and potential damage scenarios, including load-bearing capacity, deformation resistance, damage tolerance, and structural resilience. (2) Occupant comfort describes the quality of the indoor environment perceived by occupants and encompasses thermal, visual, hygric, ventilation, and acoustic conditions. (3) Energy efficiency concerns the reduction of building energy use while maintaining required indoor environmental and operational conditions.

Classification and definition of application hierarchies

Based on the implementation of biological principles in buildings, this study classifies building biomimetic applications into three hierarchies: configuration, material, and device. Building configuration refers to the translation of biological forms or spatial and structural arrangements into the geometry or organization of buildings or their components. Material refers to the development of materials with compositions, microstructures, or surface properties inspired by biological principles to enhance their intrinsic properties. Device refers to a functional building unit or system that reproduces a biological operating mechanism to perform a specific building task. Each study was assigned to a single primary application hierarchy based on the main object and mechanism of the biomimetic intervention rather than its intended building function. Representative biological prototypes and their corresponding architectural translations for each hierarchy are presented in Figure S3.

Data extraction and standardization

Study characteristics were extracted for each publication, including geographic location, application hierarchy, biological prototype, and performance indicators (Table S1). Reported performance data exhibit substantial heterogeneity in indicators, baseline definitions, and reporting formats due to the absence of a unified quantitative framework in building biomimetics research. Performance effect sizes and the corresponding research methods were systematically extracted and compiled in Table S2. The tools associated with each method are summarized in Table S6. To enable consistent quantitative synthesis, all reported effect sizes were standardized by performance objective and unit, with positive values uniformly indicating performance improvement. Three effect-size categories were defined accordingly: relative percentage improvement in structural safety indicators; percentage reductions in cooling, HVAC, and total loads; and absolute temperature reductions in thermal performance indicators. The respective calculation formulas are provided below.

For structural-safety performance indicators expressed as relative increases, the effect size was defined as

$$E_{increase} = \frac{X_{biomimetic} - X_{reference}}{X_{reference}} \times 100\%. \quad \text{(Equation 1)}$$

For the building load reduction indicators, cooling load refers to cooling demand alone; HVAC load includes heating, ventilation, and air-conditioning demands; and total load follows the aggregate load boundary reported in each original study, which may include lighting and other equipment loads. Each load reduction was expressed as a percentage of the corresponding reference load:

$$E_{reduction} = \frac{L_{reference} - L_{biomimetic}}{L_{reference}} \times 100\%. \quad \text{(Equation 2)}$$

Here, X denotes the structural performance indicator and L denotes the relevant load. The subscripts identify the biomimetic and reference conditions reported in the original study. Positive effect values indicate performance improvements.

Daytime cooling refers to the reduction in surface or cavity temperature under the biomimetic condition relative to the corresponding reference condition. It was expressed as an absolute temperature difference (°C) rather than a percentage reduction. Reported temperature reductions were extracted directly. The effect size was calculated as

$$\Delta T = T_{reference} - T_{biomimetic}. \quad \text{(Equation 3)}$$

Here, $T_{reference}$ and $T_{biomimetic}$ denote temperatures measured for the same target, either a surface or a cavity, under the reference and biomimetic conditions, respectively. Positive values indicate cooling.

Multiple results from the same study were classified by performance indicator, application hierarchy, and climate zone. When the same indicator was reported over multiple periods, the result covering the longest period was prioritized. Results sharing all three classifications were averaged into a single representative effect value. Those differing in any classification were retained as separate entries and assigned equal weight within the relevant analyses. Reported means were preferred. When only a range was available, its midpoint, calculated as the arithmetic mean of the lower and upper bounds, was used as a representative effect value. This procedure was restricted to ranges describing the same performance indicator for the same study object within the same study, application hierarchy, and climate zone. Applying this rule consistently avoided the selective use of either the highest or lowest reported effect. The midpoint was treated as an approximation when a reported mean was unavailable. Studies lacking sufficient quantitative information for standardization were excluded from the quantitative analysis but retained for qualitative synthesis.

Meta-analysis and effect quantification

A two-stage meta-analysis was conducted to synthesize the quantitative performance evidence across studies, comprising an overall synthesis (Tables S7 and S8) and subsequent subgroup analyses (Tables S9–S13). Processed effect entries were assigned equal weight within each analysis. Relative subgroup weights determined circle size in the forest plots. Mean effects summarized reported improvements under the original study conditions. Sample variances and standard errors were calculated from the contributing entries within each group, with 95% confidence intervals (CIs) based on the t-distribution. In the main text, results are reported as means ± the half-width of the 95% CI. Q and an associated I^2 index were calculated as dispersion measures using count-based weights, as detailed in Methods S2. They were interpreted alongside sample sizes, CIs, and differences in study conditions.

ACKNOWLEDGMENTS

The work described in this paper was sponsored by the National Natural Science Foundation of China (#52394223). All copyrighted materials included in this

study have been reproduced or adapted with appropriate permissions or under applicable Creative Commons licenses. The corresponding permissions and licenses are documented in Table S16. Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of those organizations.

DECLARATION OF INTERESTS

All authors have reviewed and approved the final manuscript and declare that no financial or personal relationships could have influenced the work reported in this paper.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.ynexs.2026.100173.

REFERENCES

1. Al-Obaidi, K.M., Azzam Ismail, M., Hussein, H., et al. (2017). Biomimetic building skins: An adaptive approach. Renew. Sustain. Energy Rev. 79, 1472-1491. https://doi.org/10.1016/j.rser.2017.05.028.
2. López, M., Rubio, R., Martín, S., et al. (2017). How plants inspire façades. From plants to architecture: Biomimetic principles for the development of adaptive architectural envelopes. Renew. Sustain. Energy Rev. 67, 692-703. https://doi.org/10.1016/J.RSER.2016.09.018.
3. Soltan, D.G., and Li, V.C. (2018). Nacre-inspired composite design approaches for large-scale cementitious members and structures. Cem. Concr. Compos. 88, 172-186. https://doi.org/10.1016/j.cemconcomp.2018.02.006.
4. Ubaid, J., Wardle, B.L., and Kumar, S. (2020). Bioinspired Compliance Grading Motif of Mortar in Nacreous Materials. ACS Appl. Mater. Interfaces 12, 33256-33266. https://doi.org/10.1021/acsami.0c08181.
5. Chen, S.M., Wen, S.M., Zhang, S.C., et al. (2024). Biological and bioinspired Bouligand structural materials: Recent advances and perspectives. Matter 7, 378-407. https://doi.org/10.1016/J.MATT.2023.11.013.
6. Kuru, A., Oldfield, P., Bonser, S., et al. (2021). Performance prediction of biomimetic adaptive building skins: Integrating multifunctionality through a novel simulation framework. Sol. Energy 224, 253-270. https://doi.org/10.1016/J.SOLENER.2021.06.012.
7. Uchiyama, Y., Blanco, E., and Kohsaka, R. (2020). Application of Biomimetics to Architectural and Urban Design: A Review across Scales. Sustainability 12, 9813. https://doi.org/10.3390/SU12239813.
8. Verbrugghe, N., Rubinacci, E., and Khan, A.Z. (2023). Biomimicry in Architecture: A Review of Definitions, Case Studies, and Design Methods. Biomimetics 8, 107. https://doi.org/10.3390/BIOMIMETICS8010107.
9. Fu, S.C., Zhong, X.L., Zhang, Y., et al. (2020). Bio-inspired cooling technologies and the applications in buildings. Energy Build. 225, 110313. https://doi.org/10.1016/J.ENBUILD.2020.110313.
10. Kuru, A., Oldfield, P., Bonser, S., et al. (2019). Biomimetic adaptive building skins: Energy and environmental regulation in buildings. Energy Build. 205, 109544. https://doi.org/10.1016/j.enbuild.2019.109544.
11. Jones, R.V., Fuertes, A., Scherer, R., et al. (2024). Opinion: Applications of and Barriers to the Use of Biomimicry towards a Sustainable Architectural, Engineering and Construction Industry Based on Interviews from Experts and Practitioners in the Field. Biomimetics 9, 470. https://doi.org/10.3390/BIOMIMETICS9080470.
12. Monteleone, A., Rodonò, G., Gagliano, A., et al. (2021). SLICE: An Innovative Photovoltaic Solution for Adaptive Envelope Prototyping and Testing in a Relevant Environment. Sustainability 13, 8701. https://doi.org/10.3390/su13168701.
13. Fan, Q., Zhang, X., Chen, C., et al. (2024). Biomimetic versatile wood hybrids with gradient structure towards lightweight, high strength, fire-retardant, and deterioration-resistant materials. Compos. B Eng. 280, 111483. https://doi.org/10.1016/j.compositesb.2024.111483.
14. Shen, J., Zhang, X., Yang, T., et al. (2016). Characteristic study of a novel compact Solar Thermal Facade (STF) with internally extruded pin-fin flow channel for building integration. Appl. Energy 168, 48-64. https://doi.org/10.1016/j.apenergy.2016.01.021.
15. Prihar, A., Gupta, S., Esmaeeli, H.S., et al. (2024). Tough double-bouligand architected concrete enabled by robotic additive manufacturing. Nat. Commun. 15, 7498. https://doi.org/10.1038/s41467-024-51640-y.
16. He, Z.H., Xu, Z.D., Wang, W.D., et al. (2025). Unidirectional shaking table test and nonlinear analysis on a novel viscoelastic bio-inspired multi-dimensional vibration isolation device. J. Build. Eng. 103, 112074. https://doi.org/10.1016/j.jobe.2025.112074.
17. Dong, E., Yuan, H., Chen, Y., et al. (2025). Printing large size eggshell-shaped elements with ultra-high-performance concrete: From material design to structural bearing capacity assessment. Constr. Build. Mater. 462, 139983. https://doi.org/10.1016/j.conbuildmat.2025.139983.
18. Zheng, L., Zuo, Y., Li, X., et al. (2022). Biomimetic Swallow Nest Structure: A Lightweight and High-Strength Thermal Insulation Material. ACS Nano 16, 8116-8127. https://doi.org/10.1021/acsnano.2c01451.
19. Musenich, L., Stagni, A., Derin, L., et al. (2024). Tunable Energy Absorption in 3D-Printed Data-Driven Diatom-Inspired Architected Materials. ACS Mater. Lett. 6, 2213-2222. https://doi.org/10.1021/acsmaterialslett.3c01384.
20. Li, J., Wang, S., Muhammad, Y., et al. (2022). Synthesis of Hydroxyapatite-Polydopamine-Rubber powder modifier via in-situ growth strategy for the designing of HAP-PDA-RP/SBS modified asphalt. Constr. Build. Mater. 345, 128361. https://doi.org/10.1016/j.conbuildmat.2022.128361.
21. He, H., Liu, L., Liu, X., et al. (2025). Biomimetic, highly adhesive, self-repairing and fire-protective polymeric coatings for polyurethane foam. Chem. Eng. J. 519, 165179. https://doi.org/10.1016/j.cej.2025.165179.
22. Nie, X., Xiao, C., Du, Y., et al. (2017). Connection bridge effect on a DNA-like two-spiral-up-tower building. Struct. Des. Tall Build. 26, e1406. https://doi.org/10.1002/tal.1406.
23. Mumtaz, A.R., Bede Odorčić, N., Garro, N., et al. (2024). Novel Ultra-High-Performance Concrete (UHPC) Enhanced by Superhydrophobic and Self-Luminescent Features. Sustainability 16, 1068. https://doi.org/10.3390/su16031068.
24. Xiao, Y., Zhang, W., Sun, W., et al. (2023). Preparation of hydrophobic shaped core–shell phase change pellets and thermoregulation effect in buildings. Appl. Therm. Eng. 222, 119923. https://doi.org/10.1016/j.applthermaleng.2022.119923.
25. Wang, D., Peng, H., Yu, B., et al. (2020). Biomimetic structural cellulose nanofiber aerogels with exceptional mechanical, flame-retardant and thermal-insulating properties. Chem. Eng. J. 389, 124449. https://doi.org/10.1016/j.cej.2020.124449.
26. Jamei, E., and Vrcelj, Z. (2021). Biomimicry and the Built Environment, Learning from Nature's Solutions. Appl. Sci. 11, 7514. https://doi.org/10.3390/APP11167514.
27. Sankaewthong, S., Miyata, K., Horanont, T., et al. (2023). Mimosa Kinetic Façade: Bio-Inspired Ventilation Leveraging the Mimosa Pudica Mechanism for Enhanced Indoor Air Quality. Biomimetics 8, 603. https://doi.org/10.3390/biomimetics8080603.
28. Wang, X., Wen, G., and Wei, Y. (2024). Aerodynamic Noise Simulation of a Super-High-Rise Building Facade with Shark-Like Grooved Skin. Biomimetics 9, 570. https://doi.org/10.3390/biomimetics9090570.
29. Ulrich, K., Genter, L., Schäfer, S., et al. (2024). Investigation of the resilience of cyclically actuated pine cone scales of Pinus jeffreyi. Bioinspir. Biomim. 19, 046009. https://doi.org/10.1088/1748-3190/ad475b.
30. He, Y., Brooks, A., Li, Y., et al. (2023). Towards building homeostasis through a low-cost biomimetic synthetic foam for building surface cooling and energy saving. J. Clean. Prod. 385, 135626. https://doi.org/10.1016/j.jclepro.2022.135626.
31. Khosromanesh, R., and Asefi, M. (2019). Form-finding mechanism derived from plant movement in response to environmental conditions for building envelopes. Sustain. Cities Soc. 51, 101782. https://doi.org/10.1016/J.SCS.2019.101782.
32. Hays, N., Badarnah, L., and Jain, A. (2024). Biomimetic design of building facades: an evolutionary-based computational approach inspired by elephant skin for cooling in hot and humid climates. Front. Built Environ. 10, 1309621. https://doi.org/10.3389/fbuil.2024.1309621.
33. Anzaniyan, E., Alaghmandan, M., and Montaser Koohsari, A. (2022). Design, fabrication and computational simulation of a bio-kinetic façade inspired by

the mechanism of the Lupinus Succulentus plant for daylight and energy efficiency. Sci. Technol. Built Environ. 28, 1456-1471. https://doi.org/10.1080/23744731.2022.2122675.

34. Holstov, A., Farmer, G., and Bridgens, B. (2017). Sustainable materialisation of responsive architecture. Sustainability 9, 435. https://doi.org/10.3390/su9030435.

35. Kuru, A., Oldfield, P., Bonser, S., et al. (2020). A framework to achieve multifunctionality in biomimetic adaptive building skins. Buildings 10, 114. https://doi.org/10.3390/BUILDINGS10070114.

36. Mutlu Avinç, G., KOÇ, S.N., and Arslan Selçuk, S. (2024). Biomimetic Facade Design Proposal to Improving Thermal Comfort in Hot Climate Region. Int. J. Bus. Econ. Stud. 11, 27-39. https://doi.org/10.11113/ijbes.v11.n2.1226.

37. Sommese, F., Hosseini, S.M., Badarnah, L., et al. (2024). Light-responsive kinetic façade system inspired by the Gazania flower: A biomimetic approach in parametric design for daylighting. Build. Environ. 247, 111052. https://doi.org/10.1016/j.buildenv.2023.111052.

38. Jiang, H., Guo, X., Song, J., et al. (2025). Self-adaptive integration of photothermal conversion and storage via fly ash nanocomposites with biomimetic broccoli-like structure. J. Build. Eng. 112, 113719. https://doi.org/10.1016/j.jobe.2025.113719.

39. Bermejo-Busto, J., Martín-Gómez, C., Zuazua-Ros, A., et al. (2017). Performance simulation of heat recovery ventilator cores in cascade connection. Energy Build. 134, 25-36. https://doi.org/10.1016/j.enbuild.2016.11.014.

40. Hubert, T., Dugué, A., Vogt Wu, T., et al. (2022). An Adaptive Building Skin Concept Resulting from a New Bioinspiration Process: Design, Prototyping, and Characterization. Energies 15, 891. https://doi.org/10.3390/en15030891.

41. Leung, E.M., Colorado Escobar, M., Stiubianu, G.T., et al. (2019). A dynamic thermoregulatory material inspired by squid skin. Nat. Commun. 10, 1947. https://doi.org/10.1038/s41467-019-09589-w.

42. Bui, D.K., Nguyen, T.N., Ghazlan, A., et al. (2021). Biomimetic adaptive electrochromic windows for enhancing building energy efficiency. Appl. Energy 300, 117341. https://doi.org/10.1016/j.apenergy.2021.117341.

43. Jumabekova, A., Berger, J., Hubert, T., et al. (2023). A state-space model to control an adaptive facade prototype using data-driven techniques. Energy Build. 296, 113391. https://doi.org/10.1016/j.enbuild.2023.113391.

44. Ren, T., and Yao, H. (2024). Okra functional biomimetic composite phase change materials integrated with high thermal conductivity, remarkable latent heat, and multicycle stability for high temperature thermal energy storage. Energy 308, 132934. https://doi.org/10.1016/j.energy.2024.132934.

45. Zhuo, H., Li, Q., Mei, X., et al. (2025). Leaf-Inspired Biomimetic Aerogels for Thermal Insulation in Extreme Environments. Small 21, e2501682. https://doi.org/10.1002/smll.202501682.

46. Du, F., Zhu, W., Yang, R., et al. (2023). Bioinspired Super Thermal Insulating, Strong and Low Carbon Cement Aerogel for Building Envelope. Adv. Sci. 10, 2300340. https://doi.org/10.1002/ADVS.202300340.

47. Liu, X., Xiao, C., Wang, P., et al. (2021). Biomimetic Photonic Multiform Composite for High-Performance Radiative Cooling. Adv. Opt. Mater. 9, 2101151. https://doi.org/10.1002/adom.202101151.

48. Cai, C., Chen, W., Wei, Z., et al. (2023). Bioinspired "aerogel grating" with metasurfaces for durable daytime radiative cooling for year-round energy savings. Nano Energy 114, 108625. https://doi.org/10.1016/j.nanoen.2023.108625.

49. Cheng, Z., Han, H., Wang, F., et al. (2021). Efficient radiative cooling coating with biomimetic human skin wrinkle structure. Nano Energy 89, 106377. https://doi.org/10.1016/J.NANOEN.2021.106377.

50. Zhang, X., Li, X., Wang, F., et al. (2022). Low-Cost and Large-Scale Producible Biomimetic Radiative Cooling Glass with Multiband Radiative Regulation Performance. Adv. Opt. Mater. 10, 2202031. https://doi.org/10.1002/ADOM.202202031.

51. Wang, Y., Zheng, Y., Li, W., et al. (2025). Bio-inspired thermoelectric cement with interfacial selective immobilization towards self-powered buildings. Sci. Bull. (Beijing) 70, 1994-2003. https://doi.org/10.1016/J.SCIB.2025.03.032.

52. Huang, M.C., Xue, C.H., Bai, Z., et al. (2025). Bioinspired smart dual-layer hydrogels system with synchronous solar and thermal radiation modulation for energy-saving all-season temperature regulation. J. Energy Chem. 101, 175-190. https://doi.org/10.1016/j.jechem.2024.09.051.

53. Fecheyr-Lippens, D., and Bhiwapurkar, P. (2017). Applying biomimicry to design building envelopes that lower energy consumption in a hot-humid climate. Archit. Sci. Rev. 60, 360-370. https://doi.org/10.1080/00038628.2017.1359145.

54. Webb, M. (2022). Biomimetic building facades demonstrate potential to reduce energy consumption for different building typologies in different climate zones. Clean Technol. Environ. Policy 24, 493-518. https://doi.org/10.1007/s10098-021-02183-z.

55. Nassar, A., and Abufarha, A.G.E. (2024). Systematic review turning existing Egyptian residential buildings in green ones. Innov. Infrastruct. Solut. 9, 237. https://doi.org/10.1007/S41062-024-01524-3.