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EXPLORING MULTI-LEVEL BIOMIMICRY IN BUILDING FAÇADE CONSTRUCTION

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ABSTRACT

The built environment consumes about 75% of the world's energy, and building facades are a key component in controlling heat, light and energy exchange. Biomimicry is becoming a popular design approach for sustainability, but its use at various scales in building façade design is not yet fully developed. This study aims to fill this gap by systematically reviewing the literature using Google Scholar, Scopus, Web of Science and Emerald databases, using specific keyword searches to identify and analyse peer-reviewed studies. Based on the defined inclusion criteria (English-language, peer-reviewed articles published between 2013 and 2025 on biomimicry and façade performance), a total of 46 relevant sources were selected. The review explores the potential for three levels of biomimicry – organism, behaviour and ecosystem – to be applied to the design of building façades to meet performance targets that include thermal performance, daylighting, solar control, energy efficiency and carbon reduction. Bio-inspired structures like cactus-rib geometry at the organism level can decrease the solar heat gain by 20-50%. The principles of termite-mound ventilation and stomata-inspired kinetic panels at the behaviour level can save 35% and 85.5% of energy, respectively, and enhance daylighting. Coral inspired materials decrease the embodied carbon by up to 48.76% at the ecosystem level. A conceptual framework is created that connects biological inspirations, levels of biomimicry and façade performance targets to a structured design instrument, which offers practitioners a systematic and evidence-based approach to bio-inspired façade design.

Keywords: *Biomimicry; Bio-inspired Building Façades; Building Performance Targets; Energy Efficiency; Multi-Level Biomimicry.*

1. INTRODUCTION

The built environment consumes a large portion of global energy and contributes to greenhouse gas emissions, which has raised concerns about sustainability and environmental impact (Al-Obaidi et al., 2022). The built environment consumes 75% of the global energy consumption (Gursel et al., 2023) and building components and structural materials are significant contributors to greenhouse gas emissions (Zhong et al., 2021). The energy consumption and emissions are also greatly influenced by non-structural elements like façades, interiors, and windows (Gursel et al., 2023).

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The building façade is the main interface between the indoor and outdoor spaces, which controls heat, light, moisture, air flow and aesthetics (Faragalla & Asadi, 2022). Façades are a significant factor in the energy gain or loss of buildings (Gonçalves et al., 2024) and are a key element in the way that natural light is directed into interior spaces (Balafoutis, 2025). Furthermore, façades improve the aesthetic value and adapt to the changing climatic conditions (Athauda et al., 2023). The design of the façade is one of the most important aspects to consider when meeting performance targets, such as energy efficiency, daylighting, solar control, thermal performance, and carbon reduction (Cucuzzella et al., 2023; Minaei, 2025; Rahubadda et al., 2025).

Biomimicry, which involves copying the forms, processes and systems found in nature to solve design problems, is a potential approach to improving façade performance (Shan & Junghans, 2023). Zari and Hecht (2020) state that knowledge of natural organisms and systems can be used to develop more adaptable and resilient buildings. Bio-inspiration can be used in the construction industry in two ways: design inspired by biology (top-down) and biology influencing design (bottom-up) (Othmani et al., 2022). Moreover, biomimicry can be studied at three different scales: organism, behaviour and ecosystem, which can enhance the efficiency and performance of building façades (Faragalla & Asadi, 2022).

The aim of this literature review is to critically examine existing knowledge on biomimicry in architectural design, with a particular focus on multi-level biomimicry applications in building façades, in order to identify relevant biological principles, design strategies, and performance outcomes. Based on this synthesis, the review seeks to establish the theoretical foundation necessary for developing a conceptual framework for integrating multi-level biomimicry into façade design to enhance environmental responsiveness and energy efficiency in buildings. To fill this gap, the contribution of each level to thermal comfort, energy efficiency, daylighting, durability and sustainability should be evaluated (El-Rahman et al., 2020; Hassan et al., 2023; Sheikh & Asghar, 2019; Zaki, 2023). Therefore, the purpose of this study is to establish a conceptual framework that connects biological inspirations, levels of biomimicry, and building façade performance targets, and to create a structured design tool for bio-inspired façade design.

2. RESEARCH METHODOLOGY

A systematic literature review was used to identify key concepts of biomimicry, performance targets of building façades, and bio-inspired façade applications, which were used to inform the development of a conceptual framework. The review was conducted in three stages, (1) database searching and source selection, (2) screening, and (3) data extraction and synthesis, as shown in Figure 1.

Google Scholar, Scopus, Web of Science, and Emerald were the four databases searched. The main search terms used were: "Biomimicry AND Building facades", "Building facades AND Performance targets", "Biomimicry OR Biomimetic AND Building facades", and "Building facades AND Performance targets OR Performance". Only publications in English and peer-reviewed were searched. The studies published from 2013 to 2025 were given priority to ensure the studies are current, and seminal studies published earlier were also included if relevant. Conference abstracts, non-peer-reviewed sources, and studies that were not relevant to the façade performance or biomimicry level were excluded.

Following the initial screening of titles and abstracts, 46 sources were included for full-text analysis. The sources cover various fields such as architecture, building engineering, environmental science, and materials science, and are geographically distributed in Asia, Europe, Africa, the Middle East, and the Americas. Key performance targets were taken from the literature, and the conceptual framework was developed to communicate the synthesised results.

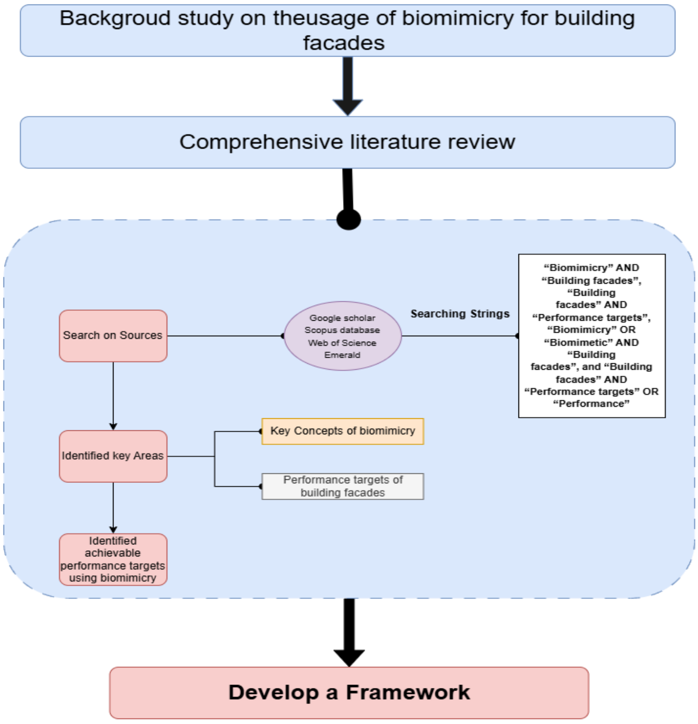

Figure 1: Research methodology

3. RESULTS AND FINDINGS

3.1 LEVELS OF BIOMIMICRY

Biomimicry has become an important design approach in architecture, enabling designers to draw upon nature to address technical and environmental challenges (Jamei & Vrcelj, 2021). It is generally perceived at three levels: organism, behaviour, and ecosystem, each with a different view of how natural systems can guide architectural design (Panjwani & Sahu, 2023). These levels are not only the basis for the development of innovative architectural forms but also enable sustainable practices by incorporating biological logic into the selection of materials and structural optimisation (Bijari et al., 2025).

3.1.1 Organism Level

Biomimicry in architecture is inspired by the shape, form and structure of living organisms like plants, animals and natural elements at the organism level (Panjwani & Sahu, 2023). This method involves incorporating physical characteristics from the natural world into architectural design, which can manifest as facades, roofs, or interior layouts that mimic natural forms and enhance their performance (Panjwani & Sahu, 2023). For example, architects can use the curvature of shells, the structure of leaves, or the lightweight yet strong skeletal structures of animals to design efficient and visually appealing structures (Bijari et al., 2025). This level focuses on the organism itself, making it possible to directly apply natural shapes and structures to the built environment, where designers can integrate functionality with nature-inspired creativity (Panjwani & Sahu, 2023).

3.1.2 Behaviour Level

At the behaviour level, instead of copying the shape or structure of nature, imitate the ways living things work and interact with their surroundings (Panjwani & Sahu, 2023). The model examines how natural systems control the flow of energy, the movement of water, the thermal stability, and adapts these processes to architectural applications (Panjwani & Sahu, 2023). According to Panjwani and Sahu (2023), a typical example is the application of termite mound ventilation principles to design buildings with a greater degree of natural ventilation and lower energy demand. In the same way, biomimetic approaches have led to the development of water management systems that emulate either the root system of plants, or hydrological patterns found in nature, in design for architecture to harvest rainwater and minimize runoff (Bijari et al., 2025). By replicating these adaptive behaviours, architects can create buildings that not only better respond to their immediate environment but also contribute to resource efficiency and sustainability (Bijari et al., 2025).

3.1.3 Ecosystem Level

The ecosystem level of biomimicry consists of using sophisticated interactions in the ecosystems and the physics (Jamei & Vrcelj, 2021). On such a scale, architects observe the interdependence of the living systems and the balance of the ecosystem in their adaptive and circular nature (Panjwani & Sahu, 2023). For example, designs can blend into the surrounding landscapes, promote biodiversity, or represent the principles of the circular economy, like minimisation of waste generation and resource cycling (Bijari et al., 2025). Buildings constructed using this paradigm are not self-contained buildings, but active members of their ecosystems, which develop symbiotic relationships with their native flora, fauna, and environmental processes (Cucuzzella et al., 2023). According to Bijari et al. (2025) A further benefit of ecosystem-level biomimicry is its ability to integrate features found in organism and behavior level approaches, resulting in integrated solutions for sustainability outcomes.

3.2 BUILDING FAÇADES: FUNCTIONS AND PERFORMANCE TARGETS

The first elements that the outside world sees are the facades, which are the architectural style and the architect's vision (Tantawy, 2023). The word "façade" comes from Vulgar Latin and means "front" or "face", as it is the main visual element of a building (Cucuzzella et al., 2023). In addition to their visual appeal, façades play a crucial role in energy efficiency by controlling heat gain and loss, managing natural light, preventing moisture infiltration, and adapting to changing climatic conditions (Athauda et al., 2023; Gonçalves et al., 2024).

The performance targets for building façades include a variety of quantitative and qualitative targets (GRESB, 2018). The U-factor is used to evaluate the thermal performance of the building envelope, which is the rate of heat transfer through the envelope (Minaei, 2025), and the thermal resistance of opaque elements is the ability of solid building elements to resist heat transfer (Shen et al., 2014). Daylighting performance is assessed by Daylight Autonomy (DA) which is the percentage of occupied hours during which sufficient daylight illuminance is provided without artificial lighting, and Work Plane Illuminance (WPI) which is the amount of daylight illuminance at the working surface (Hegazy et al., 2013; Troup et al., 2019). The window-to-wall ratio is used to evaluate solar control, and it is directly related to the amount of solar heat gain and daylighting in a façade (Gadelhak & Lang, 2016). The energy efficiency is measured by Total Source Energy Consumption (Troup et al., 2019), Lighting Source Energy (Maleki & Dehghan, 2020), Heating Source Energy, and Cooling Source Energy (Eisazadeh et al., 2018). Carbon reduction is assessed by taking into account the carbon emissions from the production and construction of materials (embodied carbon) and the carbon emissions generated during the building's occupied life (operational carbon) (Rahubadda et al., 2025).

3.3 APPLICATIONS OF BIOMIMICRY IN BUILDING FAÇADES ACROSS LEVELS

The use of biomimicry in the design of building facades has been used to achieve sustainable performance at all three levels (Jamei & Vrcelj, 2021). The Gherkin Tower in London is inspired by the Venus flower basket sponge, which optimises wind deflection and natural ventilation, and uses 20% less material than a conventional building, with a diagrid structural system (Sun, 2024). The Esplanade Theatres in Singapore are covered with aluminium sunshades that are patterned after the durian fruit, which helps to minimize solar heat gain and artificial lighting (Sidhu & Singh, 2021). The multi-layered timber louvres at Council House 2 in Melbourne are inspired by tree bark, enhancing energy efficiency and reducing the effects of climate change (Helmy & Aboulnaga, 2020). Furthermore, morphological textures inspired by elephant skin have been used to realize passive thermoregulation in hot and dry climates (Hays et al., 2024), and bio-inspired ventilated façades have been demonstrated to decrease energy consumption by 20–55% (Alyahya et al., 2025).

The Eastgate Centre in Harare, Zimbabwe, is an example of a building that uses termite-mound ventilation principles to achieve passive cooling, which results in a 35% reduction in energy consumption compared to buildings of similar size and type that are conventionally air-conditioned, and a 10% reduction in capital costs (Sun, 2024). The kinetic screen of Al Bahar Towers in Abu Dhabi is based on the concept of Mashrabiya, which is an adaptive shading system inspired by the cactus flower, to minimize the solar heat gain and enhance thermal comfort (El-Abedin et al., 2022). Likewise, adaptive façades based on stomata mechanisms have shown an 85.5% daylighting performance improvement using kinetic panel systems (Farmani et al., 2025).

The Sahara Forest Project in Jordan is based on the water-harvesting mechanisms of desert ecosystems, specifically the Namib Desert beetle, which extracts moisture from fog and uses it to grow desert vegetation (Hammond, 2023). The Pearl River Tower in Guangzhou, China, is inspired by sea sponge ecosystem principles to optimise airflow and water efficiency (AlAli et al., 2023). Algae-panel bio-façades sequester CO2 and actively mitigate carbon emissions (Metwally, 2025), and carbon-sequestration materials inspired by corals reduce embodied carbon by up to 48.76% (Rahubadda et al., 2025).

3.4 INTEGRATING MULTI-LEVEL BIOMIMICRY TO ENHANCE FAÇADE PERFORMANCE

Biomimicry levels in building façade design result in compounded performance benefits in thermal, energy and environmental aspects (Moghaddam et al., 2023). As shown in

Table 1, bio-inspired façades at the organism, behaviour and ecosystem levels can deliver measurable improvements in multiple performance targets simultaneously. Organism-level designs focus on structural optimisation and solar shading, whereas designs that incorporate behaviour-level principles include dynamic environmental responsiveness. These benefits are expanded to regenerative and carbon-sequestering outcomes at the ecosystem level (Bijari et al., 2025).

Table 1: Performances achieved using levels of biomimicry in building facades

Level	Description	Example in Building Facades	Inspiration	performance	References
Organism	Mimics forms and structures of individual organisms for static optimization	Gherkin Tower	Venus flower basket sponge for wind reduction and ventilation	Reduced material usage (20% less steel)	(Sun, 2024)
		Esplanade Theatres	Durian fruit for shading and heat block	Less energy usage for lighting	(Sidhu & Singh, 2021)
		Council House 2	Tree bark for multi-layered shading	Mitigates climate change mitigation, Energy Efficiency	(Helmy & Aboulnaga, 2020)
Behaviour	Replicates dynamic processes and environmental interactions for adaptability	Eastgate Centre	Termite Mound for Ventilation	Reduce 35% of energy consumption and save 10% on the capital cost	(Sun, 2024)
		Al Bahar Towers	Cactus flower for adaptive shading	Improve user comfort through natural lighting and thermal comfort	(El-Abedin et al., 2022)
Ecosystem	Emulates full system interactions for regenerative and holistic integration	Sahara forest project	Inspired by the desert ecosystems	Removal of moisture from fog to regenerate dry lands on an ecosystem scale	(Hammond, 2023)
		Pearl River Tower	sea sponge ecosystem for air/water flow	Achieving water and energy efficiency	(AlAli et al., 2023)

The research has shown that bio-inspired façades that incorporate all three levels of biomimicry perform better than those that use only one level of biomimicry (Bijari et al., 2025). Furthermore, the three levels can be used as a conceptual framework to guide designers in choosing the right biological inspiration for the desired performance goals

(AlAli et al., 2023). For example, bio-inspired ventilated façades can reduce energy consumption by 20-55% when inspired by both organism and behaviour level (Alyahya et al., 2025).

3.5 CONCEPTUAL FRAMEWORK FOR BIO-INSPIRED BUILDING FAÇADE DESIGN

The conceptual framework (Figure 2) is derived from two key design approaches in biomimicry identified in the literature review, the bottom-up and top-down approaches. The bottom-up approach is knowledge-driven and starts from existing biological inspirations, studying the biological principles and translating them into façade design strategies. This method is not always the best way to solve the real performance problems of a building, however. The bottom-up approach, on the other hand, is problem-driven and starts with the building performance requirements, including thermal performance, daylighting, solar control, energy efficiency, and carbon reduction. The biological inspirations that are relevant are then chosen according to their capability to solve these performance problems, leading to a more performance-oriented bio-inspired façade design approach.

The middle section of the framework shows how building performance goals, biological inspirations, and various degrees of biomimicry relate to each other during the design process. It demonstrates that various performance objectives can be achieved through different biological inspirations and biomimicry levels. Inspirations from the physical shape or surface of organisms are examples of organism-level biomimicry, and inspirations from resource cycles, energy flows, and regenerative environmental systems are examples of ecosystem-level biomimicry.

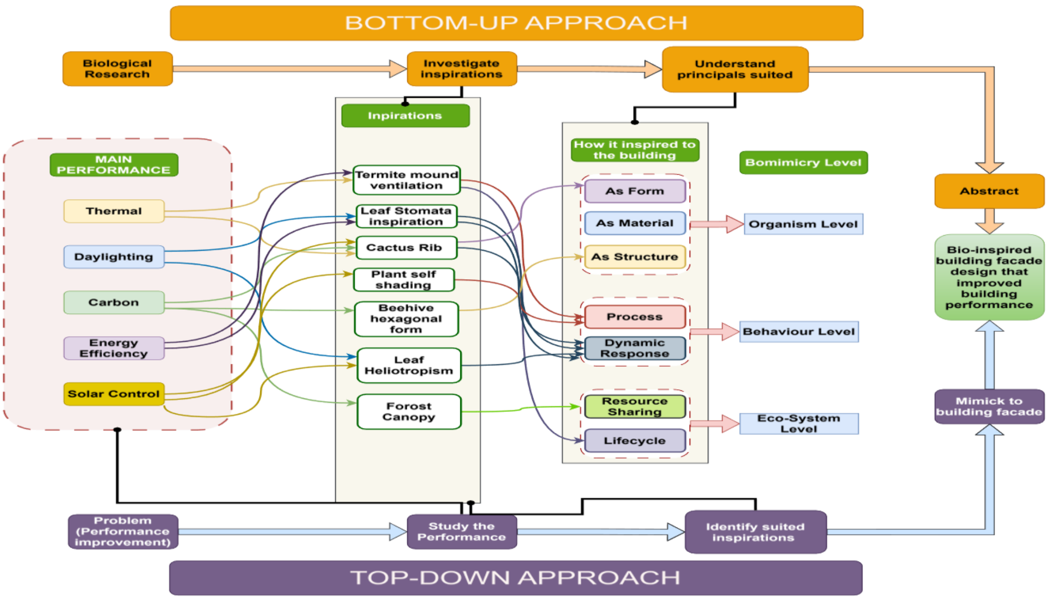

Figure 2: Proposed conceptual framework for the integration of multi-level biomimicry in building façade design to achieve enhanced environmental and energy performance

The review demonstrates that multi-level biomimicry provides an effective approach to improving building façade performance, with the integration of organism, behaviour, and ecosystem levels producing greater benefits than any single level alone (Bijari et al., 2025).

Organism-level biomimicry enhances structural efficiency and passive solar control through the replication of biological forms, as seen in the Gherkin Tower's sponge-inspired diagrid system (Sun, 2024). However, these solutions are generally static and cannot adapt to changing environmental conditions.

Behaviour-level biomimicry addresses this limitation by enabling dynamic responsiveness. Examples such as the termite-inspired ventilation of the Eastgate Centre and stomata-inspired kinetic façades demonstrate significant energy savings and improved daylight performance (Sun, 2024; Farmani et al., 2025). Despite these advantages, such systems often involve greater design complexity and maintenance requirements.

Ecosystem-level biomimicry adopts a holistic approach by integrating buildings into ecological cycles through innovations such as coral-inspired carbon-sequestering materials and algae-panel bio-façades, contributing to carbon reduction goals (Metwally, 2025; Rahubadda et al., 2025). However, these technologies remain largely emerging and face challenges related to scalability and regulatory compliance.

A common limitation across all levels is the lack of context-specific performance data under varying climates and building conditions. Future research should focus on empirical simulations and post-occupancy evaluations across diverse climatic regions, while practitioners and policymakers should promote the integration of multi-level biomimicry into early-stage design and supportive regulatory frameworks.

4. CONCLUSIONS AND RECOMMENDATIONS

This study establishes that multi-level biomimicry encompassing the organism, behaviour, and ecosystem levels constitutes a valid and evidence-based approach to improving building façade performance across five key targets, thermal performance, daylighting, solar control, energy efficiency, and carbon reduction. The systematic literature review confirms that each level contributes distinct performance benefits, organism-level inspirations improve structural and solar performance; behaviour-level approaches enable dynamic environmental responsiveness; and ecosystem-level strategies facilitate regenerative and carbon-sequestering outcomes.

The conceptual framework developed in this study advances existing knowledge by integrating biological inspirations, biomimicry levels, and performance targets into a unified, structured design instrument. By accommodating both top-down and bottom-up design approaches, the framework supports systematic, performance-oriented decision-making and addresses the gap in multi-level biomimicry evaluation identified in the literature (Hassan et al., 2023). The framework enables practitioners to move beyond isolated, single-level applications and leverage the compounded benefits of multi-level bio-inspired façade design, a shift with significant implications for the sustainability of the built environment.

The broader significance of these findings lies in their applicability across the full spectrum of façade design decision-making: from material selection and form generation to adaptive mechanism design and ecosystem integration. As the building sector faces intensifying pressure to meet net-zero targets, multi-level biomimicry offers a nature-tested, evidence-based path forward. Future work should focus on empirical validation across diverse climatic contexts, integration of the framework into building information modelling workflows, and exploration of the regulatory and economic conditions necessary to enable widespread adoption.

Further research is required to develop a comprehensive framework for the design and construction of multi-level integrated biomimetic façades. Such a framework should provide practical guidelines for combining organism, behaviour, and ecosystem-level strategies within a single façade system. In addition, future studies should evaluate and validate whether this integrated approach delivers significant improvements in energy efficiency, environmental performance, and overall building sustainability compared with single-level biomimetic applications.

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