Mimicking Nature, Empowered by Technology: A Biomimetic Approach to Sustainable Building Envelopes

Mozhgan Karimi[1], Samaneh Safaripoor[2], Negin Hamidi[3], Marjan Ilbeigi[4*]

[1] Department of Architecture, Islamic Azad University, Qeshm branch, Iran

[2] Department of Architecture, Islamic Azad University, Bandar abbas branch, Bandar abbas, Iran

[3] Christopher C. Gibbs's College of Architecture, University of Oklahoma, Norman, USA

[4] Department of Architecture, Chalous Branch, Islamic Azad University, Mazandaran, Iran

***Corresponding author**

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ABSTRACT

In the face of mounting environmental concerns and rising energy demands, this study explores the convergence of biomimicry and technology in architectural façade design. Drawing from natural adaptive strategies, biomimetic architecture offers ecologically attuned, energy-efficient, and user-centric solutions. Employing analytical methods, this research reviews international case studies such as Council House 2 (Australia), Water Cube (China), and Esplanade Theatres (Singapore), examining bio-inspired strategies across organism, behavioral, and ecosystem levels. A synthesized design matrix highlights key performance criteria including energy savings, ventilation, and adaptability. Findings demonstrate how nature-inspired and tech-enabled designs foster scalable, sustainable façade innovations

Keywords: Biomimicry, Architecture, Sustainable Design, Technology, Building Envelope, Parametric Design, AI

INTRODUCTION

Nature is an emotional element of the surrounding environment and an important aspect of coping with daily life, influencing everything around humans. Humanity has always maintained a connection with nature. Since the advent of constructing and utilizing shelters, nature has been an essential and fundamental part of planning and design (Panahi et al. 2013). Nature serves as an inexhaustible source of inspiration for scientists and engineers across various fields. Every organism is unique and perfectly adapted to its specific environment (Bayat et al. 2022). By responding to its needs and finding effective solutions, nature evolves a process that spans countless generations, undergoing the test of survival to reach its next stage (Behrouzifard et al. 2023). The field of biomimicry, which draws on plants, animals, or entire ecosystems as the basis for imitative design, has gained global attention in architecture and engineering. This is due to its potential to inspire innovative ideas and create a more sustainable environment (RMA El-Zeiny 2012). Many scientific fields are returning to nature for inspiration, and numerous studies and research projects are conducted with this approach, a concept initiated by Janine Benyus in 1997(Benyus 1997). Today, many researchers work in this area, recognizing nature as a profound source of inspiration (Hamidi et al. 2024). The built environment significantly impacts ecological systems and energy consumption. With global resource pressures intensifying, architects increasingly turn to nature—a model of adaptive efficiency refined over 3.8 billion years. Biomimicry, the practice of emulating natural forms, processes, and ecosystems, has emerged as a compelling approach to sustainable design. Unlike earlier architectural movements that viewed nature aesthetically, biomimicry regards it as a technical mentor and performance model. This paper investigates how biomimicry, supported by digital technologies, can be harnessed in the design of sustainable building envelopes.

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The art of studying and mimicking nature to achieve solutions for human needs is not a novel approach. Early humans relied on nature for food, shelter, and other indigenous innovations for survival and existence. Many of these innovations have gained recognition in fields such as medical and pharmaceutical sciences. Architecture, weapons and defense systems (e.g., armor, sensors, and warning systems), agriculture, food production, and construction processes all reflect nature-inspired advancements (Murr 2015). Through observation and in-depth study of nature, early scientists and innovators were able to gather valuable insights into functional systems and sustainable resource utilization. The natural world continuously transforms and sustains itself by meeting its needs and providing sustainable solutions for its challenges. This is the outcome of 3.8 billion years of evolution, making nature an extraordinary model for achieving harmony, balance, efficiency, collaboration, resource optimization, and longevity (Benyus 1997). Although their sustainability may not always be proven, the following initiatives stand among iconic nature-inspired innovations in early stages:

- The proposed design of flying machines by Leonardo da Vinci (1452–1519), also known as ornithopters, where he cited bats, kites, and birds as his sources of inspiration. Although da Vinci only sketched ornithopters and never built them, the first successful flight of a manned glider was recorded in 1942. Since then, achievements in manned, robotic, and electric flying vehicles have been documented.

- Sir Joseph Paxton's design of the Crystal Palace in London, constructed in Chatsworth, England, in 1851, inspired by the large leaves of the Amazonian water lily (Hashem et al. 2022).

As illustrated in Figure **1**, three contemporary architectural typologies—bionic architecture, green architecture, and kinetic architecture—utilize nature and technology to create more sustainable and environmentally friendly designs. These architectural subsets aim to reduce energy consumption and greenhouse gas emissions while enhancing human comfort and well-being, ultimately leading to sustainable design practices.

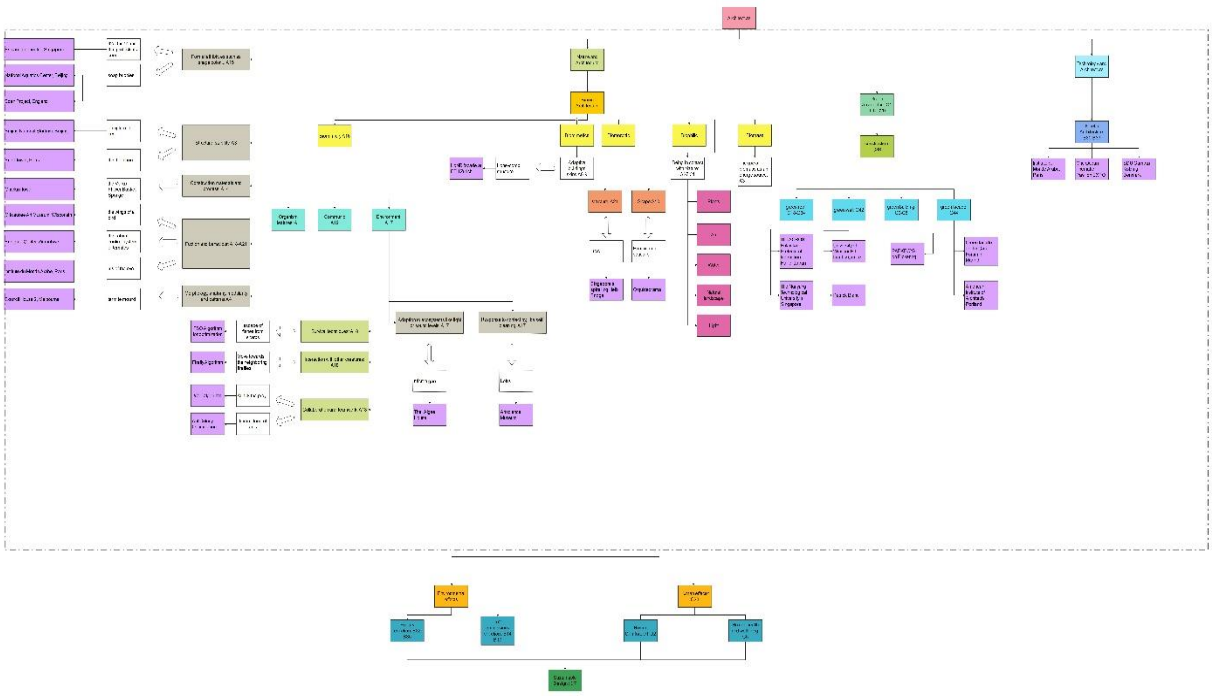

Fig1. Overview Diagram of Nature and Technology Applications in Architecture

The main objective of this study is to examine the role of nature and technology in architecture by analyzing constructed case studies. To achieve this goal, the following research questions are posed:

What are the limitations and opportunities in applying biomimicry to architectural façades?

How can digital tools enhance the integration of nature-inspired strategies?

Theoretical Foundations

Bionic Architecture

Designing with nature in the built environment can be understood through various terms, such as biomimicry, bionics, bio-design, bio morphism, bio-fabrication, biophilia, and bio-derived innovation. Biomimicry was introduced by Forough and Galapoulos, who provided a specific concept of resemblance to ecosystems by balancing nature and humanity. Benyus (Benyus J. 2002) describes biomimicry as a new orientation in science that links sustainable solutions and innovation with industrial research and development, based on ecological criteria for assessing the sustainability of our inventions. Benyus emphasized the importance of perceiving nature as a mentor, measure, and model for evaluating the application of biomimicry. Over recent decades, numerous explorations have been undertaken to investigate the development of biomimicry in architecture. One such approach involves terminology analysis by Gruber, who explored the relationship of biomimicry in biology and its potential application in built environments (Gruber et al. 2010). Pawlyn explored concepts derived from nature (Pawlyn 2019), while Gamage, Hyde, and Zari examined biomimicry based on ecosystem interactions (Zari 2010; Gamage and Hyde 2012).

The term "biomimicry" gained prominence in 1997 through the widely published book *Biomimicry: Innovation Inspired by Nature*, authored by Janine M. Benyus, a biologist, writer, and co-founder of the Biomimicry Institute. She is recognized as a pioneer in this emerging field of study (Goss 2009). The terms biomimicry and biomimetics originate from the Greek words *bios* (life) and *mimesis* (imitation). This imitation involves studying nature's models, systems, processes, and elements to derive solutions for human challenges. Although various forms of bio-adaptive or biologically inspired design have been discussed among researchers and practitioners in sustainable architecture, the widespread practical application of biomimicry as an architectural design method remains largely unrealized (Faludi 2005). This process is defined as creating sustainable designs and solutions through the conscious study and emulation of nature's forms, processes, and ecosystems (Singh and Nayyar 2015). Biomimicry is considered a branch of life sciences that interacts with various terms, emphasizing that scientific knowledge in biomimicry serves as a tool through which nature is studied (Temesgen and Ojo 2020). The transition from exploiting nature to learning from its forms, processes, and strategies marks a promising shift (Muijsenberg 2023). Over the years, nature has developed remarkable attributes for survival, efficiency, and functionality. Biomimicry leverages this abundant resource to achieve its primary goal: sustainability. Biomimicry encompasses a wide spectrum of nature-derived design thinking, including bionics, biophilic design, and ecosystem modeling. Rooted in the work of Janine Benyus (1997), it promotes viewing nature not as a resource to be exploited, but as a guide for sustainable innovation. Biomimetic strategies operate across three levels: organism, behavior, and ecosystem. Frameworks such as Benyus' "Nature as Model, Mentor, and Measure" and Zari's termite analogy offer structured approaches for translating biological insights into architectural systems.

Emerging tools such as parametric modeling and AI algorithms now facilitate complex bio-derived forms, enabling performance-based iterations that were previously unfeasible. For example, software like Grasshopper and Ladybug can simulate climate-responsive morphologies inspired by flora and fauna.

Advantages and Challenges: Bionic and kinetic architecture demonstrate the tangible benefits of biomimetic design: enhanced thermal regulation, reduced energy demand, and material efficiency. However, challenges persist. Effective biomimicry requires interdisciplinary collaboration and advanced computational skills. Material limitations, software complexity, and the lack of standard guidelines can hinder implementation. Table **1** demonstrates Framework for Biomimetic Application and The Termite Example.

- **Nature as Mentor, Model, and Measure**

1. **Nature as Mentor:**

   This perspective involves valuing nature as a resource for learning rather than an object for uncontrolled exploitation. Biomimicry encourages a new way of observing and appreciating nature.

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2. **Nature as Model:**

It studies the forms, processes, systems, and strategies of nature, imitating or drawing inspiration from them to address human problems in a sustainable manner.

3. **Nature as Measure:**

Utilizing 3.8 billion years of evolution, nature's quality control and environmental standards offer valuable benchmarks for determining the sustainability of innovations. Nature has already learned what works sustainably. Biometrics applies these environmental standards to assess the "rightness" of human innovations.

Table 1. Framework for Biomimetic Application: The Termite Example**,** (Zari 2007)

Level	Form	Material	Structure	Process	Function
Organism Level	The building resembles a termite in appearance.	The building is made from the same material as the termite, such as materials mimicking the exoskeleton.	The building is constructed in the same way a termite grows, for example, passing through growth cycles.	The building operates like an individual termite, efficiently producing hydrogen through metagenomics.	The building functions like a termite within a larger context, recycling cellulose waste to create soil.
Behavior Level	The building appears to be constructed by termites, similar to a termite mound.	The building is made from the same material as a termite mound, for instance, using pre-digested soil as a base.	The building is constructed in the same way termites build, such as periodically stacking soil.	The building mimics the behavior of termites, including orientation, material selection, and ventilation.	The building functions like a termite mound, regulating internal conditions for thermal stability and efficiency.
Ecosystem Level	The building resembles an ecosystem inhabited by termites.	The building uses materials similar to those found in termite ecosystems, such as natural compounds and water.	The building is assembled like an ecosystem evolves, applying succession principles and increasing complexity.	The building operates like the termite ecosystem, harnessing solar energy or storing water.	The building functions like a termite ecosystem, participating in hydrological, carbon, and nitrogen cycles, and forming part of an interconnected system.

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In the context of the influence of design and biomimicry, two main perspectives can be considered: design inspired by biology and biology influencing design. Design Inspired by Biology known as the top-down perspective or problem-driven biologically inspired design, begins with identifying a specific human need and observing how organisms or ecosystems solve similar challenges. In this method, designers define the problem and turn to nature for solutions. Biologists then match these challenges with organisms that have already developed solutions. Designers effectively guide this process by identifying key design objectives and parameters (Dash 2018). Biology Influencing Design referred to as the bottom-up perspective, solution-driven biologically inspired design, or biologically informed design, focuses on identifying specific behaviors or functional characteristics in organisms or ecosystems and integrating them into human design. Here, biological knowledge directly influences human design. This process involves biological research through the study of biomechanics, functional morphology, and the anatomy of specific organisms, understanding their principles, and applying them to derive a design solution (Aziz and El sherif 2016).

Principles of Biomimicry

The fundamental principles of biomimicry, as outlined by (Rowland 2017), include:

1. Efficiency in Materials and Energy

   This principle emphasizes the skillful and conservative use of resources and opportunities. It includes four sub-principles:

   - Multi-functional Design: Addressing multiple needs with a single, well-suited solution.
   - Low-Energy Processes: Minimizing energy consumption by reducing temperature and optimizing processes.
   - Recycling Materials: Ensuring that all materials are reused effectively.
   - Form Follows Function: Selecting shapes or patterns based on specific needs.

2. Evolution for Survival

   This principle involves three sub-principles:

   - Repetition of Effective Strategies: Reusing successful approaches.
   - Integration of the Unexpected: Incorporating mistakes into processes that lead to new forms and functions.
   - Exchange of Information: Sharing and modifying information to develop new options.

3. Adaptation to New Conditions

   - Adapting and evolving to suit changing circumstances.

4. Development Through Evolution

   - Advancing through evolutionary processes.

5. Harmony and Responsiveness to Locality

   This principle emphasizes alignment with the surrounding environment and includes five sub-principles:

   - Use of Locally Available Materials: Building with abundant and accessible resources.
   - Utilization of Accessible Energy: Harnessing renewable energy, such as solar power.

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- Fostering Collaborative Relationships: Encouraging cooperative interactions.
- Adopting Cyclic Processes: Utilizing circular methods for resource sustainability.
- Incorporating Feedback Loops: Using feedback mechanisms for continuous improvement.

These principles underpin the application of biomimicry, enabling innovative, sustainable, and efficient design solutions aligned with natural systems. Table **2** provides an in-depth classification of biomimicry levels, highlighting how various aspects of organisms, their societal relationships, and their interactions with the environment can inspire design and innovation.

Table 2. Levels of Biomimicry Information, (El-Zeiny 2012)

Biomimicry Levels	Aspects of the Level
Organism Characteristics	- Morphological properties: shape, color, rhythm, etc. - Organization and hierarchy of components and systems. - Structure, stability, and resistance to gravity. -Building materials and processes - Mutation, growth, and life cycle. - Functionality and behavior. - Movement and aerodynamics - Morphology, anatomy, modularity, and patterns - Portability and dynamism - Self-assembly - Repair, restoration, survival, and maintenance. - Homeostasis: balancing internal systems amidst changing external forces - Internal systems, including digestive, circulatory, respiratory, skeletal, muscular, nervous, excretory, sensory, and motor systems
Organism-Society Relationship	- Survival techniques. - Interaction with other organisms - Knowledge transfer and education - Community member hierarchy - Group management and coordination - Communication - Self-protection - Sensing, response, and interaction. - Risk management
Organism-Environment Relationship	- Contextual adaptation. - Adjustment to changes.

	- Response to climate (e.g., cooling, heating, and ventilation solutions). - Response to context (e.g., camouflage, self-protection, and self-cleaning). - Adaptation to ecosystems, including light/sound levels, shading, and self-illumination. - Shelter construction. - Management of limited resources (e.g., water, light, food scarcity, and waste management). - Input/output/process cycles.

Advantages of Bionic Architecture

The primary advantage of bionic architecture is its reliance on renewable materials, enabling more sustainable living. Additionally, it offers economic benefits due to enhanced energy efficiency, leading to reduced greenhouse gas emissions and, consequently, lesser harm to the environment (Kashkooli et al. 2011). For example: BIQ (Bio-Intelligent Quotient) House in Germany, Designed by Splitterwerk Architects and SSC Strategic Science Consultants, this house is entirely powered by algae. It serves as a heat exchanger by cultivating microalgae within its glass panels, which are used as a source of energy and heat for the building. This design generates zero-carbon electricity and is twice as efficient as photovoltaics (Nazareth 2018). also, Sahara Forest Project in Tunisia, inspired by the Namibian fog beetle, this greenhouse project can regulate the building's temperature and produce fresh water in arid climates. Like the beetle, the building uses a system of evaporation, cooling, and humidification of saline water suitable for year-round cultivation. The extracted salt from the evaporation process can crystallize into calcium carbonate and sodium chloride, creating compressed building blocks and minimizing waste (Yeang and Pawlyn 2009).

Green Architecture

Green architecture stems from sustainable architecture and sustainable development, responding to the adverse effects of industrialized and consumer-driven societies. The approach emphasizes preserving natural resources, preventing air and environmental pollution, protecting the ozone layer, and ensuring physical and mental well-being for future generations(darban and Javadnia 2018).

Key considerations in green architecture design include:

- Minimizing the overall size of the building.
- Energy-efficient buildings using high-level insulation and strategically placed windows for solar gain.
- Utilizing natural cooling systems.
- Installing solar water heaters or photovoltaic systems.
- Optimal use of recycled materials and maintaining standard ceiling heights.
- Implementing rooftop water disposal systems to collect rainwater.
- Maximizing the use of plants (Ragheb et al. 2016).

Kinetic Architecture

In contemporary architecture, kinetic, dynamic, adaptive, interactive, intelligent, responsive, and adaptable designs have become prevalent (Turrin et al. 2011; Barozzi et al. 2016). Interest in interactive, responsive, and intelligent architecture began in the 1960s and 1970s, driven by advancements in computer science and

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building technology, which transformed architecture from static forms to dynamic and kinetic designs. Early Designs: In 1908, Thomas Gaynor designed a rotary building, though it was never constructed (Randl 2008). In 1935, Angelo Invernizzi built the "Villa Girasole," a two-story, L-shaped house that rotates to follow the sun, with a 44-meter basin base and a 42-meter central tower (Alter 2017). In 1958, Friedman introduced the "Mobile Architecture Manifesto," questioning architects' authority to decide for residents. In 1959, he proposed "Spatial City Planning," where residents could modify spaces flexibly, suggesting adaptable infrastructure with movable walls, floors, and ceilings (Emanuel 2016).

In the 1960s, Gordon Pask and other cybernetics experts introduced "Conversation Theory," recognizing architectural spaces and users as feedback systems (Pickering 2010). John Frazer and Price further emphasized architecture as a "living and evolving" entity, working with students on evolutionary design concepts. Key Publications: Early works include Archigram’s "Plug-in City" (1967) and Nicholas Negroponte’s *The Architecture Machine* (1970). William Zuk and Roger H. Clark defined kinetic architecture in their 1970 book, *Kinetic Architecture*, as a system responsive to applied forces, facilitated by technology (Phocas 2013). The 21st century marked a turning point for kinetic architecture, with many designs realized. Notable examples include: Kinetic Wall at Brisbane Airport Parking Garage, Designed by Australian artist Ned Kahn in 2011, the building features a vertical façade of 250,000 aluminum panels that move with the wind (Figure **2**). This motion creates dynamic sunlight patterns inside the building. The roof design consists of eight panels opening like a camera diaphragm, adding visual and functional appeal. This evolution of kinetic architecture highlights its transformative potential, integrating movement, interaction, and adaptability into built environments.

Fig 2. Kinetic Wall at Brisbane Airport Parking Garage,www.designboom.com

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Integration of Nature and Technology

The construction industry can mitigate its environmental impact by employing technologies and materials adhering to principles of true sustainability. Numerous biomimetic materials, innovations, and patented technologies have emerged. Some multifunctional materials inspired by nature include: Super hydrophobicity, High adhesion, Self-cleaning properties, Self-healing capabilities, Thermal insulation properties, Self-assembly mechanisms, Anti-reflective surfaces, Sensory aid mechanisms, High mechanical strength, Pigmentation and color control, Aerodynamic lift and Energy conversion and conservation. Table **3** illustrated that Nature-Inspired Strategies Enhanced by Technology in buildings.

Table 3: Nature-Inspired Strategies Enhanced by Technology, (Sai Harsha and Sree Lakshmi 2020)

No.	**Product/Technology/Innovation**	**Inspired by Nature**	**Function**	**Problem Solved**
1	Dye-Sensitized Solar Cells	Photosynthesis	Produces low-cost, efficient electricity through artificial photosynthesis.	Eco-friendly solar panels.
2	Eastgate Building, Harare, Zimbabwe	Termite mounds	Night cooling, thermal storage, and convection airflows regulate temperature, reducing energy costs (heating and cooling).	Adapts easily to external temperature changes.
3	Hot Zone Radiant Heater with Irlens	Lobster	Provides concentrated point heating directed toward the user.	Efficient energy utilization.
4	bioWAVE	Seaweed	Harnesses wave energy for electricity production.	Directional wave energy capture.
5	BioLytix System	Earth's ecosystem	Water filtration and purification system.	Engineered soil system for water management.
6	COMOLEVI Forest Canopy	Tree shade	Creates a cooling effect inspired by leaf design.	Mitigates overheating.
7	Eco-Machine	Forest ecosystems	A chemical-free wastewater treatment device.	Wastewater management.
8	SageGlass, Quantum Glass (Europe)	Bobtail squid, hummingbird	Smart electrochromic windows for energy savings.	Reduces cooling/heating energy costs.
9	Aquaporin Membrane Technology	Lipid bilayers in living cells	Membrane filtration technology for safe drinking water.	Achieves filtration with minimal energy consumption.
10	Eco-Friendly Cement	Sea snail	Carbon-reinforced, neutral-weight	Reduces CO_2 emissions

			cement.	during production.
11	Chaac-ha	Bromeliad spider	Rain and dew harvesting system.	Water rejuvenation.
12	Self-Healing Concrete	Animal and human skin	Enables rapid and effective self-repair.	Prevents deterioration of concrete structures, addressing pollution, resource depletion, and energy use in traditional concrete production.

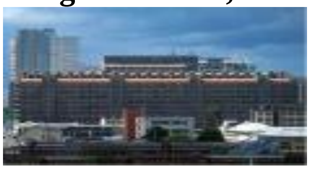
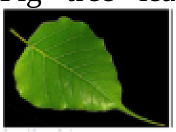
LITERATURE REVIEW

Myers' approach advances the concept of mimicry by integrating real biology into buildings to create novel forms. Mazzoleni explored methods of using animal skins for façade designs (Mazzoleni 2013). However, biomimetic research faces challenges in developing effective design tools for the built environment. Various academic studies, such as "BioSkin," "Toward a Living Façade," and "Architecture Follows Nature," have introduced strategic methods for integrating biomimicry (Badarnah and Annual 2015; Gruber et al. 2019). Several architectural projects have applied biomimicry. For instance: Flectofins (Inspired by Strelitzia reginae) was the first project drew inspiration from the pollination mechanism of the bird-of-paradise flower, Strelitzia reginae. This façade employs a reversible material deformation mechanism triggered by external mechanical forces. The adaptive approach is prominently used in an external shading system (Lienhard and Schleicher 2011). Moreover, Thematic Pavilion (Inspired by Plant Movements) was the second project is based on plant movements and mechanisms, such as those found in Flectofins. The pavilion in Korea features an adaptive shading system that responds to sunlight conditions throughout the day (Knippers and Speck 2012). HygroSkin (Inspired by Pine Cones) counted as the third project leverages movements observed in pine cones, which react passively to humidity changes. This pavilion interacts with its environment through its material's responsive capacity, utilizing relative humidity as a driver (Menges and Reichert 2012).

Royall highlighted several issues in biomimetic implementation, such as difficulties in separating methodologies from core problem-solving and the tendency to oversimplify biomimicry into a linear process (E Royall 2010). Similarly, Vogel argued that mimicking natural technology without modification leads to many unsuccessful projects (Vogel 2013). El Ahmar (2011) identified multiple challenges in biomimicry. Firstly, Biomimicry heavily relies on specific knowledge, skills, and tools. Secondly, the design approach depends extensively on computer software, which creates a gap between human and computational capabilities. Thirdly, Identifying the optimal material for a system requires numerous physical experiments and geometric descriptions. Fourthly, establishing relationships between components is complex. Fifthly, selecting appropriate algorithmic processes is crucial. besides, developing effective user interfaces for analysis and application poses a challenge. And the last challenges, Continuous evaluation and feedback control are essential (El Ahmar 2011).

Jalali and Golabchi (2018) in order to Addressing the issue of over-extraction of materials, which contributes to unsustainability in the construction industry, this research investigates material optimization strategies inspired by nature. Natural structures, such as human bones, extract materials gradually from their environment. The study proposes a prefabricated intelligent structure capable of self-repair and growth by absorbing materials over time. Such approaches could be beneficial in addressing the salinity crisis of the Persian Gulf and Lake Urmia. Also in another research, Lin & Meyers, (2005) examined the structure and form of abalone shells to design optimal shell structures for large spans. The shell form was analyzed using mathematical relations and reconstructed through parametric curves. The golden spiral shape of the abalone shell was calculated based on a rectangular plan, and various possible forms were introduced. These forms could be utilized as resilient structures in architecture and construction. This body of research underscores the significant potential and ongoing challenges in biomimetic design, offering insights into innovative solutions for sustainable architecture (Table **4**).

Table 4. Applications of Biomimicry in Architecture

Building Name	Inspired by Nature	Application in Design	Problem Solved	Biomimicry Level
Eiffel Tower 	Human femur 	- The external framework resembles the femur. - Network made of rivets and metal braces.	- Prevents bending and shearing from wind. - Ventilation issues resolved.	Organism Level
National Stadium, Beijing 	Bird's nest 	- ETFE panels insulate by filling small material pieces in branches. - Panels filter and provide sunlight protection.	- Façade openings enable natural ventilation. - Panels reduce dead load on the roof, are cost-efficient, durable, and recyclable.	Behavioral Level
Eastgate Center, Harare 	Termite mounds 	- Designed to draw in more air through open spaces and direct it upward via central building ducts.	- Maintains temperature year-round without HVAC systems.	Behavioral Level
HOK, Lavasa, India 	Fig tree leaves 	- Foundation stores water.	- Responds to seasonal flooding. - Moves excess water.	Ecosystem Level

RESEARCH METHODOLOGY

The research methodology employed in this study is analytical, with an evaluation of constructed examples from around the world. This section presents an analytical study of three international cases utilizing cellular biomimicry approaches in façade design. The focus is on applied technologies, techniques, and strategies to develop a design matrix that leverages the characteristics of various natural organisms to achieve the research objectives.

Case Studies

Council House 2 in Melbourne, Australia is a sustainable 10-story building located in Melbourne, Australia. Constructed between 2004 and 2006, the design of this building is highly innovative, challenging traditional sustainability and architectural design approaches by mimicking tree bark. Biomimicry is implemented throughout the building, with distinct features inspired by natural elements: Western Façade: Mimics the epidermis of a tree, inspired by its interaction with external weather conditions. also, in Northern and Southern Façades which Modeled after tree branches, functioning as wind pipes for external air ducts in CH_2. And Eastern Core and Façade: Houses service cores and restrooms, mimicking tree bark (as shown in Figure **3**). The "bark" acts as a protective layer, filtering light and ventilating air into the moist space behind it (Webb 2005). This biomimetic approach demonstrates how tree-like structures can enhance building functionality, sustainability, and environmental responsiveness.

Fig3. Wind Pipes in the Northern Façade (B) Overlapping Façade Layers, (Radwan and Osama 2016)

Case Study 2: The Water Cube (China National Aquatic Center), Beijing

The Water Cube, also known as the Beijing National Aquatics Center, was constructed between 2004 and 2007, primarily for the 2008 Olympics. The building exemplifies biomimicry by emulating the shape of soap bubbles, which are ideal for swimming environments (Radwan and Osama 2016).

Case Study 3: Esplanade – Theatres on the Bay, Singapore

This two-story building, designed by DP Architects and Michael Wilford, is located near Singapore's historic Marina Bay. The initial design faced criticism for incorporating excessive glass and adhering to a Western design approach insensitive to Singapore's tropical climate. The revised design used a biomimetic approach inspired by the tropical durian fruit. The building's façade mimics the biological anatomy of the fruit, providing shading and repetition against the region's intense heat. Completed in 2007, the design reflects bio-adaptive principles, responding effectively to the local environment and culture while avoiding excessive traditionalism(Radwan and Osama 2016). Table **5** showed the case studies of this project.

Table 5. Case Studies

Building Name	**Location**	**Inspired by Nature**	**Application in Design**	**Problem Solved**
Council House 2 (CH2)	Melbourne, Australia	Tree bark and branches	- Western façade mimics tree epidermis.	- Improved ventilation and air circulation.
			- Northern and southern façades mimic branches, acting as air ducts.	- Energy-efficient natural cooling.
Water Cube (National Aquatics Center)	Beijing, China	Soap bubbles	- Façade replicates the geometry of soap bubbles.	- Enhanced interior conditions ideal for swimming environments.
Esplanade – Theatres on the Bay	Singapore	Durian fruit	- Façade mimics durian anatomy, providing natural shading and heat resistance.	- Adaptation to Singapore's tropical climate, reducing cooling energy demands.

RESULTS

To establish guidelines for building façade design, the case studies and their objectives were compared. As shown in Table **6**, an analysis of various criteria was conducted across the three case studies to evaluate their energy efficiency and effectiveness. The symbols used in the table represent: ● Fully satisfactory, ★ Moderately satisfactory and ○ Unsatisfactory

Table 6. Comparison of Case Studies

Index	Case Study 1	Case Study 2	Case Study 3
Efficiency			
Energy Savings (%)	82%	30%	30%
Natural Ventilation and Lighting (%)	65%	55%	45%
Air Filtration	●	○	○
Interaction with Natural Environment	●	●	●
Heat Protection	●	●	●
Visual Comfort	●	●	●
Following Sun Path Chart	●	●	●
Use of Photovoltaic and Solar Panels	●	●	○
HVAC Reduction Level (%)	20%	30%	15%
Materials			
Recyclable	●	★	★
Renewable	●	★	★
Approach			
Biology-to-Design	○	○	○
Design-to-Biology	●	●	●
Biomimicry Level			
Organism	●	●	●
Behavioral	●	○	○
Ecosystem	○	○	○

The overall result is derived directly from the various criteria considered throughout the project. For instance, the use of solar panels, sun path chart analysis, visual comfort, total energy savings, HVAC savings, and natural lighting and ventilation all contribute to the final outcome. Among the case studies, Council House 2 (CH_2) proved to be the most efficient and robust example, as its overall savings surpassed the other two case studies.

Key features of CH_2 include:

- The use of highly recyclable and renewable materials.
- Comprehensive air filtration.
- Mimicking the core characteristics of a tree in terms of energy efficiency.
- Maximizing biomimetic analogies in its design.

After analyzing the case studies, it becomes essential to develop a design matrix to identify the primary requirements for façade design. The design matrix outlines the critical criteria necessary for designing energy-efficient building façades. This matrix as Table **7**, serves as a guideline for creating low-energy façades, aligning with sustainability goals and efficient resource utilization. The findings from CH_2 highlight the

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potential of integrating biomimicry, efficient material use, and energy-saving strategies into façade design, setting a benchmark for future architectural practices.

Table 7. Design Matrix

Mechanism			Behavioral Thermal	Water Efficiency &	Heat Insulation & Savings	Dynamic Behavior	Color Impact &	Water Collection &
Site		Tropical		√	√		√	
		Polar			√		√	
		Desert	√	√	√	√	√	√
Key Indicators	Communication	Color Change				√		
		Interaction with External Environment	√	√		√	√	
		Color for Absorption				√		
		User Engagement				√		
		Attracting Users	√	√		√		
	Thermal Efficiency	Heat Storage		√	√			
		Light		√	√			
		Indoor Temperature Regulation			√			
		Insulation			√			
	Water Efficiency	Reducing Water Consumption		√				√
		Water Recycling		√				√
		Water Collection		√				√
		Air Filtration		√				
		Self-Cleaning Façade		√				
	Thermal Regulation	Internal Temperature Control	√		√			
		Solar	√					

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		Protection						
		Sun Path Chart Utilization	√			√	√	
		Responsive Façade	√			√	√	
		Façade Maintenance	√	√	√	√		√
		Responding to External Environment	√	√	√	√	√	√
Inspirations			Reptiles	Plants/Flowers	Polar Animals (Bears, Penguins	Violet Flower	Geometric Patterns	Namib Desert Beetle

Case Studies and Results Three international case studies demonstrate practical biomimetic applications:

- **Council House 2 (Australia)** mimics tree structures for ventilation and insulation.
- **Water Cube (China)** uses soap bubble geometry for climate-adaptive aquatic design.
- **Esplanade (Singapore)** applies the durian fruit's anatomy for solar shading.

Performance comparisons reveal that CH2 offers the most comprehensive biomimetic integration, achieving notable reductions in HVAC loads and energy consumption.

Design Matrix A design matrix summarizes biomimetic performance criteria by climate zone, identifying mechanisms such as thermal regulation, water collection, and dynamic shading. This tool can guide future façade design with bio-adaptive strategies matched to environmental context.

CONCLUSION

Nature has sustained itself for billions of years, demonstrating remarkable energy efficiency. Architectural approaches such as green architecture, kinetic architecture, and bionic architecture are widely interconnected. While they may differ in principles, their ultimate goals are reducing energy consumption and minimizing environmental pollution. Among these, green and bionic architecture place particular emphasis on drawing inspiration from nature. Ultimately, a successful architectural design is one that skillfully emulates nature and utilizes existing technologies to create more sustainable solutions. Natural organisms have evolved strategies to conserve energy efficiently. By incorporating these characteristics into architecture, human challenges can be addressed effectively. Mimicking nature to achieve a new approach for building façades, particularly in optimizing energy consumption, holds significant potential. Building façades account for a substantial portion of energy use. By exploring and replicating nature's strategies, energy consumption can be reduced through the integration of biomimicry and technology. This reduction in energy use leads to lower greenhouse gas emissions, which contributes significantly to environmental preservation. Furthermore, it enhances human thermal comfort and health, as the well-being of individuals is intrinsically tied to the health of the environment. Biomimetic architecture presents scalable, climate-sensitive solutions for the future of sustainable construction. To accelerate adoption, we recommend:

1. **For Architects**: Employ biomimetic strategies early in the design process using parametric modeling tools like Grasshopper, Rhino, and AI-based optimization platforms.

2. **For Policymakers**: Introduce incentives and certification frameworks that support nature-based solutions in building codes.

3. **On Cost and Scalability**: While initial costs may be higher due to R&D or custom fabrication, long-term energy savings and maintenance reduction offset investments. Open-source tools and modular biomimetic components can improve scalability.

4. **Climatic and Socio-economic Adaptability**: Solutions must be tailored to local materials, climate, and socio-economic conditions. Biomimicry's versatility allows adaptation to arid, tropical, and temperate environments alike.

5. **Future Outlook**: Advancements in AI and machine learning can accelerate the identification of functional analogies in nature, enabling designers to match environmental challenges with optimized biological precedents.

By aligning biological intelligence with computational power, architects can create façades that not only perform sustainably but also resonate culturally and ecologically.

Data availability statement

Data is available per request

Disclosure statement

The authors report there are no competing interests to declare

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