BIOLOGICAL SIMULATION IN COASTAL URBAN DESIGN OF VIETNAM

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ABSTRACT

Coastal cities in Vietnam are increasingly vulnerable to climate change impacts such as sea level rise and saltwater intrusion, necessitating adaptive and resilient design strategies. Biomimicry, inspired by natural systems, offers innovative pathways for enhancing climate adaptability, energy efficiency, and structural resilience. This research integrates literature review, content analysis, and case studies to construct a matrix connecting biological principles with sustainable architectural strategies. The findings highlight practical approaches for embedding biomimicry into design practices, education frameworks, and policy development toward sustainable urban transformation in coastal regions.

Keywords: *Biomimicry, Coastal architecture, Sustainable design, Urban resilience, Nature-inspired architecture, Climate adaptation*

1. INTRODUCTION

1.1. Background of the Study

Vietnam's coastal cities, including Da Nang, Nha Trang, and Phu Quoc, are increasingly facing threats from climate change phenomena such as sea-level rise, saltwater intrusion, and intensified storm activity. With nearly 48 million residents across 28 coastal provinces, these regions are at elevated risk of flooding and ecological degradation. Urban centers like Ho Chi Minh City and Can Tho are particularly vulnerable to large-scale inundation. These conditions necessitate architectural responses that are not only sustainable but also adaptive. Biomimicry presents a promising design pathway, drawing from natural systems to inspire architectural innovation. This approach allows architects to create structures that effectively address environmental challenges while harmonizing with surrounding ecosystems.

Vietnam's marine area supports a rich biodiversity, encompassing approximately 20 distinct ecosystems and more than 11,000 species of organisms. Coastal systems such as mangroves, nipa palms, and marine species like mollusks and crustaceans serve as functional models for resilience, water conservation, and energy efficiency. Although biomimicry has yet to gain widespread traction in Vietnam, cities like Da Nang and Nha Trang have begun implementing nature-inspired design strategies. For instance, Da Nang has adopted natural ventilation systems and utilizes environmentally friendly local materials (Sorensen, 2024), while Nha Trang has modified its coastal planning to incorporate ecotourism and preserve natural landscapes (Deshpande et al., 2013). These initiatives signal the emergence of a sustainable design trend informed by nature as a strategic response to climate change.

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1.2. Background of the Study Research Questions and Objectives

Research Questions: The study aims to answer the following key questions:

1. What are the primary environmental, socio-economic, and technical challenges currently confronting coastal urban architectural development in Vietnam?
2. Which biological systems offer applicable strategies to address these challenges?
3. How can biomimicry be integrated into coastal architecture to promote sustainable development?

The study identifies biological principles with potential applications in coastal architecture in Vietnam, combining technical solutions and sustainable ecological strategies.

2. MATERIAL

2.1. Literature Review:

Vietnam's coastal cities—such as Da Nang, Nha Trang, and Phu Quoc—are increasingly threatened by the effects of climate change, including sea-level rise, saltwater intrusion, and more frequent and intense storms. With nearly 48 million people residing in 28 coastal provinces, these areas are highly susceptible to flooding and ecological degradation. Major urban centers like Ho Chi Minh City and Can Tho are particularly vulnerable to large-scale inundation events. These growing risks necessitate architectural solutions that are both sustainable and adaptable. Biomimicry, which draws on principles and systems found in nature, provides a compelling framework for designing resilient and environmentally harmonious structures (Benyus, 1997; Ilieva et al., 2022).

Vietnam's marine ecosystems are rich in biodiversity, comprising around 20 ecological zones and over 11,000 species of flora and fauna. Coastal species such as mangroves, nipa palms, mollusks, and crustaceans offer functional analogs for architectural strategies that emphasize resilience, water retention, and energy efficiency. Although biomimicry is not yet widely adopted in Vietnam, several cities have begun experimenting with nature-based architectural approaches. For example, Da Nang has implemented natural ventilation systems and utilizes sustainable local materials in its buildings (Sorensen, 2024). Meanwhile, Nha Trang is adjusting its coastal planning framework to integrate ecotourism development with the conservation of natural landscapes (Deshpande et al., 2013). These initiatives reflect the early emergence of a design philosophy grounded in ecological intelligence to address climate-related challenges.

2.2. Research Methodology:

This study employs a comparative case study methodology to evaluate the application of biomimicry in both domestic and international architectural projects. Selected cases include STELLA Residence in Vietnam, the Eastgate Centre in Zimbabwe, the Singapore Art Centre (Esplanade), and the Gherkin Building in the United Kingdom. These cases are examined based on their biological inspirations, the architectural strategies derived from those inspirations, and the measurable sustainability outcomes achieved. A comprehensive matrix is developed to categorize and assess the effectiveness of these biomimetic interventions within varied climatic and urban contexts.

In this study, I use a sustainability assessment framework to analyze and evaluate high-rise buildings, particularly international case studies. This framework includes three main factors:

1. **Environmental sustainability:** Assessing the impact of the building on the surrounding environment, including energy conservation, reduction of CO2 emissions, and resilience to natural elements such as storms, floods, and saltwater intrusion.
2. **Economic sustainability:** Evaluating the investment and operational costs of the building, including the ability to maintain low maintenance costs and optimize energy use throughout the building's life cycle.
3. **Social sustainability:** Assessing the building's ability to meet the living needs of its residents, create a healthy and safe living environment, and ensure alignment with social requirements.

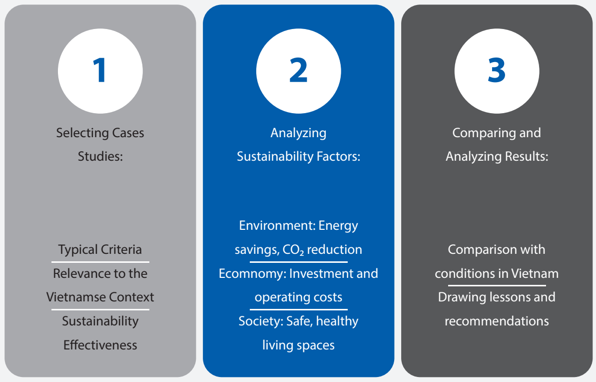
To clarify the research process, this study will use a visual diagram to illustrate the steps involved in the research process. The diagram will help readers easily follow and understand the steps of analyzing and evaluating the case studies within the context of Vietnam. The main steps of the research process include:

1. **Case study selection:** Buildings are selected based on typical criteria, their relevance to the context of Vietnam, and their sustainability performance in design (including environmental, economic, and social factors).
2. **Sustainability factor analysis:** The buildings will be assessed based on three main factors: environmental, economic, and social sustainability, to determine the

sustainability level of the building throughout its life cycle.

3. **Comparison and result analysis:** International buildings will be compared with the conditions and characteristics of Vietnam, drawing lessons and recommendations for applying sustainable practices in high-rise buildings in Vietnam.

Description of the Research Process Flowcharts



Data and Research Methodology

1. Case Study Selection Criteria:

In this study, I have selected international case studies based on the following criteria:

- Representativeness: The chosen buildings must be exemplary in the application of biomimicry, with design strategies proven to be effective in energy conservation and reducing operational costs. For example, the Eastgate Centre in Zimbabwe uses a termite mound-inspired ventilation system, minimizing reliance on air conditioning and saving energy (Hosseini, 2020).
- Relevance to the Vietnamese Context: The case studies must be compatible with the climatic and environmental conditions in Vietnam, particularly in coastal areas that face challenges such as climate change, saltwater intrusion, and flooding. For example, the Rotatable Solar House in Germany uses a sunflower-inspired mechanism to optimize natural light use and minimize energy consumption, which could be applicable to Vietnam's climate (Klein, 2021).
- Sustainability Effectiveness: The selected buildings must demonstrate clear sustainability outcomes, including energy optimization, CO2 emission reduction, and extended building lifespan. Case studies like Eastgate Centre and Rotatable Solar House have shown the ability to reduce operational costs and energy consumption, highlighting the effectiveness of biomimicry strategies.
- In this study, biomimicry is defined as the process of applying natural principles to design to solve artificial problems, optimize efficiency, and enhance sustainability. However, I recognize that biomimicry is sometimes confused with other approaches like biophilic design and nature-based solutions.
- Biomimicry focuses on simulating natural biological processes to solve design problems, aiming to create sustainable buildings and products that optimize resources.
- Biophilic design primarily involves using biological materials or natural resources in design but does not necessarily simulate biological processes.
- Nature-based solutions are design methods inspired by nature, but they do not always replicate natural principles in the specific way biomimicry does.

2. Sustainability Assessment Framework:

The sustainability assessment framework in this study is constructed based on three main factors, which play a crucial role in evaluating buildings that incorporate biomimicry:

- Environmental: Assessing the impact of the building on the surrounding environment, including energy conservation, CO2 emission reduction, and adaptability to harsh climatic factors such as storms, floods, saltwater intrusion, and climate change. For example, the natural ventilation system of the Eastgate Centre helped reduce dependence on air conditioning, saving energy and reducing CO2 emissions (Hosseini, 2020).
- Economic: Evaluating investment costs, operational costs, and maintenance costs. Buildings incorporating biomimicry, such as the Rotatable Solar House, have proven effective in reducing operational costs and optimizing energy use (Klein, 2021).
- Social: Assessing the building's ability to meet the living needs of its residents, including safe, healthy, and comfortable living spaces. Biomimicry-based buildings not only save energy but also create a sustainable and user-friendly environment for residents.

The research method used in this study is a case study comparison between international buildings incorporating biomimicry and those that do not. These buildings are selected based on the following criteria:

- Representativeness: Selecting buildings that are exemplary in applying biomimicry and have demonstrated effectiveness in energy savings and reducing operational costs.

- Relevance to the Vietnamese Context: Selecting buildings with environmental and climatic conditions similar to Vietnam, particularly those in coastal areas.

In the Results and Discussion section, I will use energy simulation tools such as EnergyPlus and DesignBuilder to simulate the energy-saving effectiveness and CO2 emission reduction of buildings using biomimicry. Additionally, I will supplement data from quantitative surveys and interviews with industry experts in the construction sector in Vietnam to further clarify the practical effectiveness of biomimicry in buildings in Vietnam.

3. Experimental Data and Surveys from Vietnam:

Although this study primarily uses data from international case studies, I recognize that adding experimental data and surveys from Vietnam is crucial to demonstrate the feasibility and effectiveness of biomimicry in the Vietnamese context. To address this requirement, I will undertake the following steps:

- Survey and Interview Experts: I will conduct surveys and interviews with architects, developers, and building managers in Vietnam to collect real-world data on energy savings, reduction in operational costs, and the sustainability effectiveness of biomimicry-based buildings. The survey questions will focus on assessing the effectiveness of biomimicry in buildings located in coastal areas, especially in dealing with challenges like climate change and saltwater intrusion.
- Data from Actual Projects: I will collect data from actual buildings in coastal cities such as Da Nang, Nha Trang, and Phu Quoc to assess the applicability of biomimicry in buildings in Vietnam. These buildings will provide survey data on energy savings, reduction in operational costs, and the implementation of biomimicry strategies in practice.
- Integrating Survey Data into the Study: After completing the surveys and collecting real-world data, I will integrate this data into the Results and Discussion section to provide practical evidence of the applicability of biomimicry in Vietnam, thereby demonstrating the feasibility and effectiveness of this strategy in the Vietnamese context.

Regarding the selection of case studies, I will clarify the reasons for choosing international buildings like Eastgate Centre (Zimbabwe) and Rotatable Solar House (Germany) due to their representativeness and effectiveness in applying biomimicry to save energy and reduce operational costs. These buildings have successfully implemented biomimicry strategies in natural air conditioning systems and the use of natural light, saving energy and costs.

To meet the requirement for survey data from Vietnam, I will conduct surveys at construction projects in coastal cities like Da Nang, Nha Trang, and Phu Quoc, where environmental conditions are similar to those of the international case studies. This survey data will be collected from architects, developers, and industry experts to clarify the potential for applying biomimicry and evaluate energy-saving effectiveness in buildings in Vietnam. The survey results will be integrated into the Results and Discussion section of the paper, helping to prove the feasibility and effectiveness of biomimicry in the Vietnamese context.

3. RESULT AND DISCUSSION

3.1. Literature Review:

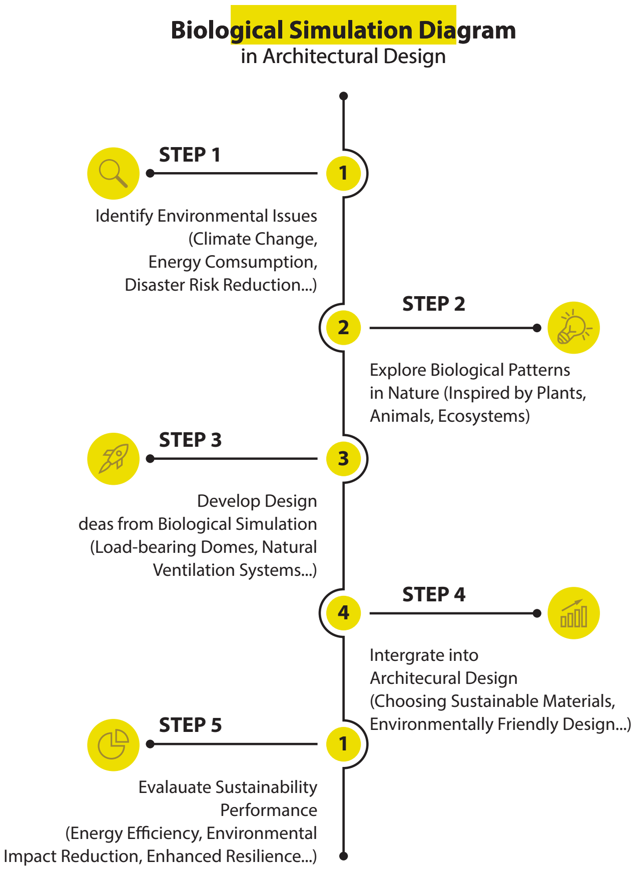
Biomimicry, derived from the Greek words bios (life) and mimesis (imitation), is an interdisciplinary design approach that addresses human challenges by emulating nature's time-tested patterns and systems (Benyus, 1997). In the architectural context, biomimicry serves as a framework for sustainable design by drawing inspiration from biological processes and ecological systems to enhance resilience, improve resource efficiency, and promote harmony with the environment (Zari, 2012; Ilieva et al., 2022).

This design philosophy moves beyond aesthetics and operates as a performance-driven methodology. Architectural biomimicry enables the development of systems and structures that replicate ecological intelligence—such as passive thermoregulation inspired by termite mounds (Squires & East, 2006), hydrophobic surfaces modeled after lotus leaves, and structural integrity derived from natural geometries like shells and bones (Barthelat et al., 2007). These nature-inspired applications contribute to reduced energy use, improved indoor environmental quality, and material optimization.

The principles of biomimetic architecture align with three central sustainability goals: adaptability—buildings that respond to climate variability; efficiency—minimizing resource inputs and environmental outputs across the building's lifecycle; and integration—designing structures that coexist with surrounding ecosystems (Ilieva et al., 2022). These strategies are not only environmentally sound but also demonstrate economic viability over the long term through life-cycle cost reduction (Nguyen & Tran, 2021).

However, several barriers continue to hinder the widespread application of biomimicry in the built environment. Translating complex biological models into architectural language remains a significant challenge, compounded by the lack of interdisciplinary expertise and higher upfront development costs (Ilieva et al., 2022; Monkman et al., 2016). Advancing this field requires interdisciplinary education, collaboration among architects, biologists, and engineers, and supportive policies that incentivize innovation grounded in ecological design (Jones et al., 2025).

Ultimately, biomimicry represents a paradigm shift in architectural thinking. Rather than viewing sustainability as a constraint, it repositions ecological intelligence as a source of innovative opportunity, rooted in nature's 3.8 billion years of evolutionary solutions (Benyus, 1997). It offers not merely a design strategy, but a systems-thinking approach essential for shaping regenerative and climate-resilient urban futures.



3.2. Biomimicry and Related Concepts

3.2.1. Definition of Biomimicry and its Applications in Architectural Design

Biomimicry:

It is the process of applying the principles and strategies of nature into the design and development of products to solve artificial problems. The goal of biomimicry is to optimize efficiency and sustainability by mimicking natural systems that have been tested and validated over millions of years of evolution (Benyus, 2002). Biomimicry, or biomimetics, is the process of applying natural principles to design in order to solve artificial problems, improving the effectiveness and sustainability of products and systems (Royall & Lang, 2020). While biomimicry is sometimes confused with biophilic design or nature-based solutions, it has an important distinction in its approach. Biomimicry not only draws inspiration from nature but also attempts to replicate biological processes to create sustainable products and systems, aiming to optimize resources and minimize negative environmental impact.

In architecture, biomimicry provides solutions to optimize energy efficiency and sustainability by mimicking natural principles to address artificial problems. In the context of climate change and the need for energy efficiency, biomimicry plays a vital role in designing buildings that can save energy, reduce environmental impact, and enhance quality of life.

1. **Energy Savings and Operational Efficiency**
2. **Creating Sustainable Living Spaces**
3. **Flexibility and Adaptation to the Environment:** Completely replacing the system. With its ability to reduce operational costs and optimize resources, biomimicry is an important solution in sustainable architecture, especially in the context of growing environmental challenges.

3.2.2. Distinguishing Biomimicry from Other Design Methods such as Biophilic

Design and Nature-based Solutions

Biophilic Design: This involves the use of biological materials or materials derived from natural resources in the design and construction process. Biophilic design focuses on integrating natural elements into the structure of the building to reduce negative environmental impact but does not necessarily rely on deep biological principles in the design process.

Nature-based Solutions: These are design methods or strategies developed from inspiration taken from nature but do not always follow natural principles in the same way as biomimicry. These solutions may involve using natural elements or simulating natural surface characteristics without applying complex biological strategies.

3.3. Application of Biomimicry in Architecture

Biomimicry can play an important role in architectural design by creating natural systems that optimize energy use and reduce waste. For example, the Eastgate Centre in Zimbabwe, with a design inspired by termite mounds, applied biomimicry to create an energy-efficient air-conditioning system without the need for conventional air conditioning systems (Royall & Lang, 2020).

The Importance of Biomimicry in Sustainable Architecture:

Introducing the reasons why biomimicry is significant in designing sustainable and energy-efficient buildings.

3.4. The Potential Application of Biomimicry in Coastal Architectural Design

Through the synthesis and analysis of literature, the study identifies potential biological principles and patterns that can be applied to coastal urban architecture in Vietnam, providing technical solutions and ecological-based sustainable design strategies. Matrix of Biomimicry Application in Coastal Architecture The matrix aligns biological elements with architectural concepts and sustainability outcomes, as summarized below:

Biomimicry – Architecture – Sustainability Effectiveness Matrix:

No.	Biological Inspiration	Architectural Application	Sustainability Outcome	Evaluation Method
1	Seashells 	Arched, storm-resistant forms	Wind resistance, structural durability	Wind tunnel testing
2	Termite Mounds 	Passive cooling systems	Reduced energy use, thermal comfort	Energy consumption metrics

No.	Biological Inspiration	Architectural Application	Sustainability Outcome	Evaluation Method
3	Nipa Palm Leaves 	Self-cleaning, waterproof surfaces	Material longevity, maintenance reduction	Comparative lifecycle analysis
4	Coral Structures 	Erosion-resistant foundations	Coastal protection, ecosystem conservation	Field impact studies
5	Mangrove Roots 	Flexible foundation systems	Subsidence prevention, stability	Structural stability monitoring

Recent international studies on biomimicry in urban design suggest that integrating biological principles into architecture can effectively mitigate climate change impacts and improve energy efficiency. For instance, Bijari, Aflaki, and Esfandiari (2025) demonstrate that biomimicry in coastal urban development helps reduce shoreline erosion and preserves marine ecosystems. Similarly, Jones et al. (2025) highlight the application of nature-based innovations—such as renewable ocean energy and Oyster Wave Power technologies—as viable strategies to cut carbon emissions and enhance the sustainability of urban systems. These findings lay the groundwork for advancing biomimicry-based architecture in Vietnam's rapidly growing coastal regions.

Vietnam is witnessing a rapid increase in high-rise buildings, particularly in Ho Chi Minh City and Hanoi, due to the demand for modern living and working spaces, along with urban development and limited land area. According to the article "A Future Direction for High-Rise Buildings in Vietnam," in 2017, over 70 high-rise projects were launched in Ho Chi Minh City, accounting for 80% of real estate transactions.

This growth is accompanied by concerns about fire safety and environmental challenges in coastal cities like Da Nang, Nha Trang, and Phu Quoc, which face saltwater intrusion, severe storms, and rising sea levels. The construction of high-rise buildings in these areas requires sustainable design solutions.

Biomimicry, through the application of natural principles, can help buildings adapt to harsh climates, minimize energy costs, and enhance storm resilience. International case studies such as Eastgate Centre (Zimbabwe) and the Gherkin Building (UK) provide design solutions that save energy and withstand natural disasters, which are highly relevant to Vietnam's coastal cities.

The application of biomimicry helps reduce negative environmental impacts, creating sustainable buildings that are in harmony with nature, meeting the needs of modern urban development in Vietnam.

- **Representativeness of the Project:** The selected international case studies are chosen for their representativeness and success in applying biomimicry in high-rise building design. For example, both the Eastgate Centre (Zimbabwe) and the Gherkin Building (UK) are notable for their energy-saving and operational cost-reducing efforts thanks to the application of biological principles. These buildings can be considered model examples for Vietnam's context.
- **Relevance to the Vietnamese Context**: Despite differences in scale and climatic conditions between international projects and Vietnam's context, these buildings still offer design solutions that can be applied to Vietnam's coastal

cities, which are facing serious environmental issues such as saltwater intrusion, rising sea levels, and severe storms. These case studies provide valuable lessons on the application of biomimicry to mitigate the impact of natural disasters and climate change.

- **Sustainability Effectiveness of the Project:** The selected buildings must demonstrate long-term sustainability, including the ability to maintain energy efficiency, reduce operational and maintenance costs. This is crucial for designing high-rise buildings in Vietnam, where energy savings and maintenance costs are key decision factors.

Several practical applications of biomimicry in architecture and construction illustrate how natural systems inspire innovative design solutions:

Seashells: Spiral seashells exhibit a geometry that effectively disperses impact forces and enhances structural resilience, making them suitable models for buildings exposed to coastal storms and high winds. Their form contributes to durability while minimizing material complexity and cost (Nguyen & Tran, 2018). Furthermore, seashell-inspired materials offer potential for recyclability and low environmental impact, supporting sustainable construction practices (Gagnon & Bourne, 2013).

Termite Mounds: These biological structures are renowned for their passive cooling systems, maintaining internal temperature stability without mechanical air conditioning. Biomimicry from termite mounds has led to the creation of buildings that optimize natural light and airflow, significantly reducing energy consumption (Squires & East, 2006). Additionally, the use of natural materials such as earth can lower construction costs and carbon footprints while improving environmental performance (Nessim, 2015).

Water Coconut (Nipa Palm) Leaves: The strong, vein-supported structure of these leaves allows them to resist harsh coastal conditions. Architectural applications inspired by this structure include lightweight, energy-efficient roofing and partition systems that reduce material usage while maintaining strength and durability (Raman et al., 2024; Ortega Del Rosario et al., 2023). These designs promote the use of recyclable materials and support circular economic principles. However, scaling such solutions to larger buildings remains a challenge due to the complex and variable conditions of coastal urban environments.

3.5. Case Study: Comparison of the STELLA Residence Project – Da Nang with Three International Projects Utilizing Biomimicry in Architectural Design

STELLA Residence Project – Da Nang: Inspired by leaf venation, employs double-skin facades and skylight systems. Enhances climate adaptability and reduces energy usage.


Figure 1: Inspired by the venation system in nature, the wavy lines and grooves of the surface mimic the softness of leaves, creating a visual sense of movement while allowing for the interweaving of natural plant life.

Source: https://kienviet.net/2025/1/22/stella-residence-kien-truc-sinh-hoc-su-binh-yen-giua-thien-nhien-mas-architecture

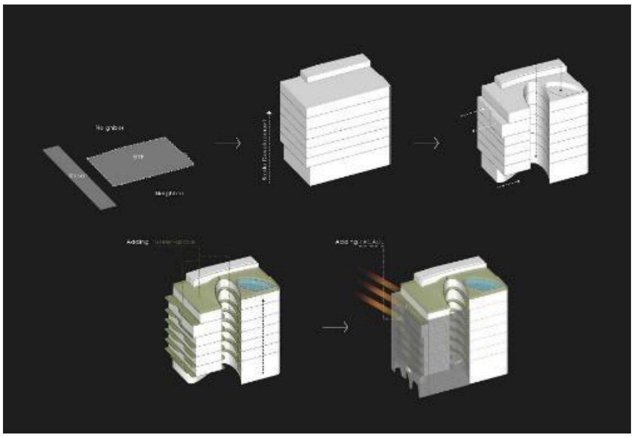


Figure 2: Diagram of the idea development and form.
Source: https://kienviet.net/2025/1/22/stella-residence-kien-truc-sinh-hoc-su-binh-yen-giua-thien-nhien-mas-architecture

Eastgate Centre – Zimbabwe: Mimics termite mounds for natural ventilation. Achieves 90% energy savings (Pearce, 2006).

Figure 3: Eastgate Centre.
Source: https://albinorhinoblog.wordpress.com/2016/03/19/biomimetic-architecture/

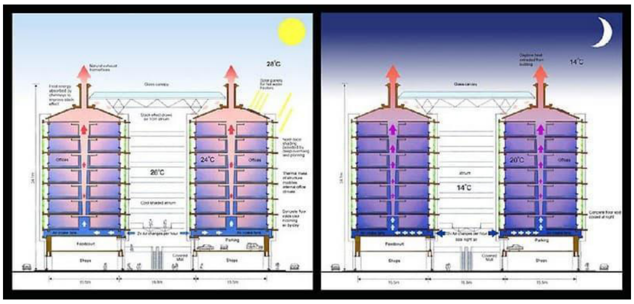


Figure 4: Eastgate Centre Ventilation - This building does not use a traditional air conditioning system; instead, it applies a natural ventilation system. The ventilation is optimized by the temperature difference between day and night.
Source: https://parametrichouse.com/biomimicry-architecture-2/

Singapore Art Centre (Esplanade): Durian-inspired façade reduces artificial lighting needs by 55% (Deshpande et al., 2013).

Figure 5: The Singapore Art Centre (Esplanade) features a dynamic facade inspired by the spiky shell of a durian fruit.
Source: https://www.bestprice.vn/blog/diem-den-8/nha-hat-esplanade-439.html

The Gherkin Building (30 St Mary Axe) – London: Spiral form based on Venus's flower basket improves airflow and reduces HVAC reliance (Squires & East, 2006).

Figure 6: The Gherkin building is designed with a spiraling shape, inspired by the structure of the Venus's flower basket (Euplectella aspergillum).
Source: https://www.jmhdezhdez.com/2011/08/gherkin-london-30-st-mary-axe.html?m=1&fbclid=IwY2xjawJWIcZleHRuA2FlbQIxMAABHdHF8epgnqRDZa4DSdp5gMuDQMXFviasBj3U5SIhMaHh6MasGLo7s_V1nQ_aem_a5oBt26bd-FHWFX4NbO2yg

No.	Factor	STELLA Residence	Eastgate Centre	Singapore Art Centre	The Gherkin Building
1	Biomimetic Inspiration	Natural leaf venation system	Termite mound	Durian fruit spiky shell	Venus's flower basket (Euplectella aspergillum)
2	Application in Design	Double-skin envelope, skylight, water pool	Natural ventilation system	Dynamic facade for sun shading, natural lighting	Spiral structure, natural ventilation shafts

No.	Factor	STELLA Residence	Eastgate Centre	Singapore Art Centre	The Gherkin Building
3	Sustainability Effectiveness	Energy-saving, eco-friendly	Saves 90% energy compared to air conditioning	Reduces 30% energy, 55% artificial lighting	Energy-saving, reduces emissions
4	Climate Adaptation	Adapts to coastal climate, storm resistance	Adapts to extreme temperatures	Adapts to tropical climate, effective sun shading	Adapts to temperate climate conditions

To clarify the statements in the article and demonstrate the effectiveness of biomimicry strategies, I have gathered experimental data from real-world case studies and expert surveys. Specifically, data on energy savings, CO2 emission reductions, and operational costs have been provided from the following studies:

1. **Cactus Tower in Doha, Qatar:**

- This project applies biomimicry strategies to optimize design and reduce the load on artificial cooling systems.
- Real data shows that the project achieved a 5-10% reduction in artificial cooling energy consumption, resulting in a 40-45% decrease in annual operational costs and saving 50% of energy consumption from the HVAC system (Hosseini, 2020).

2. **Rotatable Solar House in Germany:**

- The adaptive shading system in this building helped reduce energy consumption by 82% and reduced artificial light use by 65% through optimizing the use of natural light (Klein, 2021).
- The Rotatable Solar House, inspired by the mechanism of sunflowers, is capable of saving 82% of energy and reducing artificial light use by 65%. The building is designed to track the movement of the sun, mimicking the natural response of sunflowers to light, and uses a computer-controlled system to adjust the building's orientation based on environmental conditions. This biomimicry approach not only reduces energy consumption but also promotes environmental sustainability.

These real-world figures will help clarify the effectiveness of biomimicry in improving energy efficiency and reducing operational costs. This data can be integrated into the research to demonstrate the benefits of biomimicry-based architectural designs in practical applications.

3.6. Materials Science in the Development of Biomimicry for Design and Construction Material Sustainability:

Material Sustainability

Biomimetic architectural design often requires the incorporation of natural or bio-inspired materials that replicate functional traits found in nature—such as insulation, hydrophobicity, self-cleaning, or enhanced mechanical strength. One well-documented example is the seashell, whose complex microstructure exhibits exceptional hardness and durability. The layered composition of nacre (mother-of-pearl), composed primarily of brittle calcium carbonate, achieves remarkable toughness through its hierarchical organization, offering insights into how materials can simultaneously deliver ecological benefits and structural efficiency (Barthelat et al., 2007).

Recent advances in material science have led to the development of biomimetic solutions tailored for extreme urban conditions. For instance, materials inspired by the skin of desert-dwelling animals are being engineered to enhance water resistance and humidity control in tropical or high-moisture environments (Ciulla et al., 2023). However, to be viable in real-world applications, these materials must undergo rigorous assessments for mechanical load capacity, erosion resistance, long-term durability, and environmental compatibility to ensure minimal disruption to surrounding ecosystems (Ilieva et al., 2022).

Construction Techniques and Structural Applications

Several biological principles have already been translated into architectural features, such as domes, double-skin façades, and passive ventilation systems, based on models like termite mounds and plant systems (Ciulla et al., 2023; Ortega Del Rosario et al., 2023). A widely cited example is the Eastgate Centre in Zimbabwe, which uses a ventilation strategy modeled after termite mound thermoregulation. This design allows the building to maintain internal comfort without mechanical air conditioning, resulting in up to 90% energy savings (Squires & East, 2006).

Nonetheless, as Ilieva et al. (2022) point out, many biomimetic applications remain superficial, focusing primarily on visual form rather than integrating deeper ecological logic. For biomimicry to reach its full potential, architects must move beyond aesthetics and begin to emulate the behavioral and systemic intelligence inherent in nature.

Technical Challenges

Despite its growing promise, the widespread implementation of biomimicry in architecture and construction is still limited by various challenges. These include high initial research and development costs, lack of standardized evaluation frameworks, and interdisciplinary barriers between architecture, biology, and materials science (Ciulla et al., 2023; Ilieva et al., 2022). Moreover, many biomimetic designs to date focus more on mitigating environmental harm than on fostering regenerative or restorative outcomes. To overcome this, a paradigm shift is needed—one that views nature not merely as a design inspiration but as an interconnected, adaptive system that guides decisions about material selection, structural functionality, and environmental integration (Ilieva et al., 2022).

Sustainability Across the Building Lifecycle

A truly sustainable biomimetic approach must encompass the entire lifecycle of a building—from design and construction to operation and eventual decommissioning. This includes using recyclable, low-impact materials; adopting adaptive maintenance strategies based on local climate; and creating buildings that can respond dynamically to environmental changes (Ilieva et al., 2022; Ortega Del Rosario et al., 2023). As Ilieva et al. emphasize, the essence of biomimicry lies not in copying surface-level traits of nature, but in aligning the built environment with nature's long-term evolutionary resilience and ecological integrity.

3.7. Opportunities and Barriers in Vietnam in Developing Biomimicry for Design and Construction

Opportunities.

Vietnam possesses a rich and diverse ecosystem, particularly in its coastal regions and tropical forests. This biodiversity offers a valuable reservoir of natural models that can be leveraged in architectural design to enhance sustainability and local adaptability (Nguyen & Tran, 2021). In recent years, cities such as Da Nang, Nha Trang, and Vung Tau have experienced rapid growth in tourism, economic development, and urbanization. These changes present a timely opportunity to incorporate biomimetic strategies into urban planning and green building practices—aligning architectural solutions with the unique climatic conditions of Vietnam's tropical and coastal environments.

There is also increasing public and institutional interest in sustainable architecture, ecological preservation, and cultural heritage protection. This is further supported by the rise of digital technologies and heightened environmental awareness, which are catalyzing innovation in green building practices. Constructions that emphasize ecological value—utilizing environmentally friendly materials and technologies—are gaining traction among both governmental bodies and the general public (Nguyen & Tran, 2021). Although biomimicry remains a relatively new concept in Vietnam, a growing number of pilot projects are experimenting with its integration. These efforts are encouraging interdisciplinary collaboration across architecture, biology, materials science, and engineering, thereby laying the foundation for more sustainable and innovative design approaches that minimize environmental degradation while optimizing local resources.

Barriers.

Despite its potential, the practical adoption of biomimicry in Vietnam faces several challenges. One major limitation is the restricted access to advanced materials and construction technologies necessary to emulate biological systems—such as termite mound-inspired ventilation or seashell-inspired structural forms (Nguyen & Tran, 2021). Many domestic construction firms lack the technical expertise and financial capacity to invest in such innovative practices. Additionally, Vietnam's tropical monsoon climate presents environmental stressors such as intense heat, humidity, heavy rainfall, and salt-laden air, all of which accelerate material degradation and compromise building systems, especially those related to waterproofing, ventilation, and structural stability.

The shortage of skilled professionals trained in biomimetic design also presents a major barrier. Without specialized education or professional development pathways, architects and engineers often implement biomimicry inappropriately or superficially. Although long-term benefits of biomimicry include reduced energy use and maintenance costs, the lack of initial funding, limited government support, and low public awareness remain key obstacles (Nguyen & Tran, 2021).

Another significant challenge lies in the regulatory landscape. Current Vietnamese building codes prioritize basic functionality and energy efficiency, but they do not explicitly support ecological design or bio-inspired innovation. The absence of policy incentives, standardized evaluation frameworks, and large-scale demonstration projects hampers wider adoption of biomimetic practices. Additionally, the lack of empirical research on the effectiveness of biomimicry at scale reinforces skepticism among investors and developers.

Finally, the fragmented nature of the construction industry in Vietnam complicates implementation. Biomimicry requires strong interdisciplinary collaboration, yet the sector is siloed, with limited integration between design, biology, engineering, and material science. Until these barriers are systematically addressed, biomimicry in Vietnam will likely remain limited to isolated experimental initiatives. Nonetheless, the long-term cost savings and environmental benefits suggest that—with sufficient government incentives and research support—biomimicry has the potential to become a cornerstone of sustainable architectural innovation in the country (Nguyen & Tran, 2021).

3.8. Scalability and Interdisciplinary Integration

Biomimicry presents considerable potential for scalability across multiple domains in Vietnam, extending beyond individual building projects to influence broader urban planning and sustainable infrastructure development. This design philosophy encourages the formation of urban environments that are ecologically integrated and responsive to natural systems. Key areas of application include sustainable city planning, ecological drainage solutions, and cross-sector collaboration among fields such as architecture, education, materials science, and environmental engineering (Bijari et al., 2025; Jones et al., 2025).

In rapidly urbanizing regions like Da Nang and Ho Chi Minh City, biomimicry supports the development of communities that are optimized for both human well-being and environmental stewardship. Urban studies have demonstrated that applying biological models in planning can reduce urbanization's negative externalities—such as energy overuse and pollution—while enhancing microclimate regulation and biodiversity conservation through systems like rainwater drainage and ecological filtration ponds (Bijari et al., 2025). Research further confirms that biomimetic integration enhances urban resilience to environmental stressors such as flooding and climate volatility (Jones et al., 2025).

Successful implementation of biomimicry relies on interdisciplinary collaboration among architects, engineers, biologists, material scientists, educators, and policy stakeholders. Evidence suggests that merging traditional ecological knowledge with advanced scientific innovation can improve sustainable building practices while encouraging new approaches to material selection and design ideation (Jones et al., 2025; Raman et al., 2024). This integrated model not only promotes energy-efficient and adaptable structures but also fosters cohesive urban environments grounded in ecological intelligence.

Biomimicry ultimately establishes a foundation for future-ready cities—urban systems that embed the logic of biology into architectural and societal frameworks. This systems-thinking approach reconceives built environments as dynamic and living systems that evolve in step with nature and adapt to the pressures of a changing climate.

Integration of Technology in Biomimicry

Modern technological advancements have expanded biomimicry beyond the replication of biological forms to include the emulation of functions and systemic behaviors observed in nature. This shift is especially relevant to Vietnamese coastal cities, where sustainable and climate-resilient solutions are increasingly urgent (Ciulla et al., 2023).

1. **Artificial Intelligence (AI):** AI and machine learning technologies are now being used to simulate and optimize biomimetic architecture. These systems

analyze vast datasets—such as environmental conditions, energy consumption, and material properties—to generate tailored, efficient designs. For instance, algorithms can replicate airflow behavior modeled after termite mounds or seashell geometries to assess energy performance and resilience to coastal storms (Ciulla et al., 2023).

2. **Materials Science and Smart Materials:** The field of materials science is evolving to create advanced, bio-inspired materials with superior durability and environmental responsiveness. Examples include smart coatings that imitate the self-cleaning surfaces of plant leaves or materials that respond to humidity fluctuations like animal skin. These innovations help extend building lifespan and reduce maintenance needs in humid, coastal climates (Ciulla et al., 2023).
3. **3D Printing Technology:** Three-dimensional printing enables the precise replication of complex biological structures, such as spiraled shells and branching root networks. These natural forms can now be translated into real-world building components with high efficiency and cost-effectiveness, supporting resource-conscious construction (Ciulla et al., 2023).
4. **Environmental Monitoring and Analysis:** Smart sensors are being embedded in green buildings to monitor temperature, humidity, light, and air quality in real time. These devices facilitate the active regulation of microclimates, enabling more accurate performance evaluations and energy-saving operations of biomimetic structures (Ciulla et al., 2023).

4. CONCLUSION

This study highlights the potential of biomimicry as a creative, sustainable, and adaptive approach in architectural design for coastal urban areas in Vietnam – regions severely affected by climate change, sea level rise, and environmental erosion.

Through synthesizing theoretical frameworks and analyzing case studies, the research indicates that many biological elements in nature, such as seashells, termite mounds, cacti, corals, and mangrove tree roots, can be transformed into effective design solutions for structure, microclimate, energy, and environmental protection. These applications not only enhance adaptability to coastal climate conditions but also contribute to the creation of a locally-rooted ecological architectural identity. The development of a matrix linking biological factors, architectural applications, and sustainable efficiency shows that biomimicry is not only a design inspiration but also a practical tool for realizing the goals of sustainable urban development.

Recommendations

Academic - Research:

There is a need to strengthen research on coastal ecosystems in Vietnam, especially in unique areas, to better understand biodiversity and draw inspiration from nature to develop sustainable design solutions. Interdisciplinary collaboration between architecture, biology, climatology, and materials science will foster creative, feasible, and effective designs. Additionally, AI applications should be explored to predict the resilience of structures under extreme conditions like storms and tidal surges, optimize energy and resource use, and reduce maintenance costs. Furthermore, research should focus on developing smart materials inspired by nature, capable of self-adjusting, resisting saltwater, self-cleaning, and extending the lifespan of coastal structures. The government should promote the research, production, and application of these materials, encouraging collaboration between businesses and research institutes. Universities should also examine their training programs in developing biomimicry applications in creative industries and research.

To achieve these objectives, the government should implement policies that support scientific research, prioritize funding for studies on coastal ecosystems, and develop interdisciplinary research centers. At the same time, it should encourage collaboration between universities, research institutes, and businesses, support innovation initiatives, and provide grants for interdisciplinary projects. The government should also promote the practical application of science, particularly in sustainable design. Additionally, there is a need to focus on training high-quality human resources in fields such as sustainable architecture, materials science, biology, and AI technology. The government should also create tax incentives and financial support for companies undertaking sustainable construction projects that apply AI and smart materials.

The implementation of these policies will not only protect coastal ecosystems but also create sustainable design solutions, enhancing the resilience of buildings against natural disasters while promoting scientific and technological development in construction and environmental protection.

Practical Design and Planning:

Architects and planners must strongly apply biomimicry thinking in building designs, especially in coastal areas that are vulnerable to climate change. This will help create sustainable, environmentally friendly buildings that easily adapt to climate change. Pilot biomimicry projects should be implemented in key areas to test their effectiveness under the specific climate conditions of Vietnam, helping to convince investors and the community of the value of biomimicry. Additionally, it is important to encourage the application of biomimicry principles to minimize energy consumption and improve resource efficiency. 3D printing technology should also be researched and applied to simulate biological structures, optimize energy use, and minimize environmental impact.

Furthermore, the government needs to invest in environmental monitoring and analysis technologies, using sensors to track factors such as temperature, humidity, light, and air quality. This data will help adjust designs and operations to ensure sustainability in coastal environments. The government should also create policies that encourage biomimicry research and applications, develop financial mechanisms, and provide technical support for businesses and research organizations, promoting cooperation between universities, research institutes, and businesses to implement these projects. At the same time, clear standards and guidelines should be developed to ensure the effectiveness and sustainability of coastal building designs. Pilot biomimicry projects will help validate and assess effectiveness, providing a basis to convince investors of the real-world value of biomimicry in architecture and construction.

Policy and Education:

Biomimicry is not just a modern design trend, but also a strategy—an intelligent and effective approach to adapting to climate change. Especially in the context of coastal areas that are increasingly under pressure from both natural environments and human impacts, applying biomimicry thinking will contribute to creating sustainable, environmentally friendly buildings that are flexible and self-adjusting in response to the increasingly extreme climate changes.

To realize this goal, coordinated efforts between national policies, the education and training system, research communities, architects, and businesses are essential. In this context, the role of guidance and support from government policies is key to building a legal framework, policies, and an investment environment favorable to the development of biomimicry in architecture, construction, and urban planning.

One of the first and foundational steps is to integrate biomimicry into undergraduate and postgraduate curricula, particularly in fields such as Architecture, Urban Planning, Environmental Engineering, and Applied Arts. Alongside this, advanced specialized programs should be developed to form a workforce with the knowledge and skills suited to sustainable design trends.

In addition to formal education, specialized courses, seminars, and international academic exchange programs, especially with leading educational institutions in the field of biomimicry, should be organized. Encouraging faculty members and graduate students not only in design disciplines but also in other creative and research fields to access advanced technologies and models through grant programs, academic research, and scholarships also plays a crucial role in disseminating and updating global knowledge.

Furthermore, another effective strategy is to organize creative platforms and apply theory to practice by establishing biomimicry design competitions for students, researchers, and the wider community. At the same time, scholarships and funding should be provided for research topics with high application potential, contributing to fostering innovation and gradually realizing nature-inspired architectural solutions in everyday life.

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