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HARNESSING NATURE'S BLUEPRINT: BIOMIMICRY IN URBAN BUILDING DESIGN FOR SUSTAINABLE AND RESILIENT CITIES

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ABSTRACT

The increasing urban population and its associated activities significantly contribute to greenhouse gas emissions and exacerbate climate change impacts. Urban areas, particularly susceptible to extreme weather events, face challenges such as heat stress, flooding, air pollution, and water scarcity. In response, the concept of biomimicry, drawing inspiration from nature's functional principles, has gained traction as a viable approach for sustainable urban design. By emulating natural systems and processes, biomimetic solutions offer innovative strategies for addressing environmental challenges at various scales, from single buildings to entire urban areas. This study explores the potential of biomimicry in urban building design to mitigate environmental challenges associated with rapid urbanisation and climate change. Utilising a two-part methodology, the research includes a narrative literature review and a survey of practical case studies to evaluate the benefits of biomimetic concepts in architecture. The literature review provides a comprehensive, critical analysis of current knowledge on biomimicry, while the case studies showcase real-world examples of biomimetic design, such as the Eden Project and Eastgate Centre. Findings demonstrate that biomimicry enhances energy efficiency, reduces Carbon emissions, and increases resilience against extreme weather events. The study concludes that while biomimicry holds great promise for creating sustainable and resilient urban environments, widespread adoption is hindered by limited awareness and education among stakeholders. The research contributes to the field by highlighting the need for increased training and collaboration in biomimicry to fully harness its potential for sustainable urban design.

Keywords: *Biomimicry; Climate Change Mitigation; Resilient Urban Environments; Sustainable Architecture; Urban Built Environment.*

1. INTRODUCTION

Over half of the global population resides in urban areas, a figure expected to rise to 68% by 2050 (United Nations Department of Economic and Social Affairs Population Division, 2018). This rapid urbanisation significantly impacts climate change through direct CO_2 emissions and indirect effects such as pollution, waste production, and unsustainable consumption (Min et al., 2022). As urban populations expand, cities' influence on regional and global climates is likely to intensify (Emmanuel & Krüger, 2012). The swift growth of urban areas has led to microclimatic conditions, increasing

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local air temperatures (Fahed et al., 2020). Consequently, urban areas are highly vulnerable to climate change impacts, facing risks including heat stress, flooding, landslides, air pollution, drought, and water scarcity (Stadler & Houghton, 2020). Urbanisation correlates with global population growth, exacerbating issues such as urban flooding, which affects larger populations and causes extensive damage costing billions of dollars (Zu Ermgassen et al., 2019). Global warming, driven by fossil fuel combustion since the Industrial Revolution, has resulted in increased CO_2 emissions (Musah et al., 2021). Especially urban building construction, identified as one of the least sustainable areas, significantly contributes to the climate crisis (Sijakovic & Peric, 2021).

In response, many cities have implemented measures to combat climate change. Networks such as the C40 Cities Climate Leadership Group (C40) and Local Governments for Sustainability (ICLEI) facilitate collaboration to address climate challenges (Musah et al., 2021). The European Strategic Energy Technology Plan (SETplan) aims to convert 50% of buildings in 25 cities into nearly zero-energy buildings (ZEB) by 2020, reducing Greenhouse Gas (GHG) emissions by 40% (Kylili & Fokaides, 2015). Additionally, innovative approaches, such as biomimicry, offer promising solutions to mitigate climate impacts from the urban construction industry (Austin et al., 2020).

Biomimicry involves drawing inspiration from nature's functional principles to design objects or systems, aligning closely with natural mechanisms (Pawlyn, 2019). Its core principle is emulating natural systems or processes to solve design challenges sustainably (Ahamed et al., 2022). While biomimetic solutions may influence a building's form, their primary goal is to derive functional, sustainable solutions from nature (Dicks et al., 2021). This approach is applied across various design fields, from fabric creation to complex building systems development (Nazir et al., 2023). The human impact on the natural and built environment underscores the need for a shift in city planning and construction, aiming for sustainable cities where biomimicry is a guiding concept (Ferwati et al., 2019).

This paper explores how integrating biomimicry into urban construction can address the dual challenges of urbanisation and climate change, leading to more sustainable, efficient, and resilient urban environments. It examines building designs that have achieved environmental benefits, such as energy efficiency and reduced carbon emissions, through biomimicry. The paper is structured as follows: a literature review, a methodology section, and an evaluation of biomimicry in building designs.

2. METHODOLOGY

The methodology of this study involves a two-part literature review process. The first part is a narrative literature review, where a comprehensive, critical, and objective analysis of current knowledge on biomimicry in urban design is conducted. This review involved searching academic databases such as PubMed, Google Scholar, and JSTOR using keywords including "biomimicry," "urban design," "sustainable architecture," and "climate change mitigation." The selection criteria included peer-reviewed articles, books, and reputable industry reports published within the last decade, ensuring a focus on recent advancements and relevant studies (Palmatier et al., 2018).

The second part is a brief literature survey evaluating the benefits of incorporating biomimicry concepts in building projects. This survey involved reviewing case studies and practical examples that demonstrate improved energy efficiency, enhanced resilience, and reduced environmental impacts. The sources were selected based on their relevance and evidence of successful implementation of biomimicry principles in real-world projects. This combined approach offers a thorough overview of biomimicry's potential to transform urban environments sustainably.

3. THE CONCEPT OF BIOMIMICRY

According to Benyus (1997), biomimicry involves the replication of natural processes to foster the development of innovative and sustainable design solutions. According to Zari and Hecht (2020), Biomimicry in Ecosystem Design Strategies revolves around “The emulation of strategies seen in the living world as a basis for design and innovation and has the potential to contribute to the creation of more sustainable architecture and urban environments”. Biomimicry encompasses two primary design approaches i.e. (i) the problem-based approach, often referred to as "design to biology," and (ii) the solution-based approach, entitled "biology to design," or the bottom-up approach (Aboulnaga & Helmy, 2022). The bottom-up approach relies on design solutions initially derived from scientific discoveries by biologists, such as the self-cleaning ability observed in lotus flowers, while the problem-based approach finds inspiration in biology by matching a problem to an organism that has already solved a similar challenge (Radwan & Osama, 2016). Furthermore, the solution-based approach is employed when the design process relies primarily on the scientific expertise of biologists and scientists rather than being driven by human design challenges from the outset (Martín-Gómez et al., 2019). One potential drawback of the problem-based approach is that it may not investigate how buildings relate to both each other and the ecosystem they are part of, thereby potentially neglecting to address the underlying causes of non-sustainable or even deteriorating built environments (Nkandu & Alibaba, 2018). Nonetheless, the problem-based approach can serve as a promising starting point for initiating the transformation of the built environment from inefficiency to a more sustainable state (Januszkiewicz & Alagoz, 2020). Moving on to the solution-based approach one drawback involves the necessity for conducting extensive biological research, followed by the critical assessment of gathered information to establish its relevance in a design context (Zari & Hecht, 2020). However, one of its benefits is that biological knowledge can influence the design in ways that step beyond addressing the initially defined design problem (Nkandu & Alibaba, 2018).

3.1 BENEFITS OF BIOMIMICRY

The escalating environmental deterioration and rapid climate change necessitate the imperative incorporation of biomimicry thinking into contemporary society for knowledge, adoption, integration, and application (Jamei & Vrcelj, 2021). Biomimicry has garnered widespread popularity and proven successful across diverse academic disciplines on a global scale (Oguntona & Aigbavboa, 2023). Table 1 illustrates the primary benefits of incorporating Biomimicry features in the urban built environment.

Table 1: Benefits of biomimicry in urban built environment

Benefits of Biomimicry	Authors											
	A	B	C	D	E	F	G	H	I	J	K	L
Resource (material and energy) efficient	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sustainability	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Resilience and Adaptability	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
Cost Efficiency (Maintenance and Operating)	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	
Waste Reduction	✓		✓		✓	✓	✓	✓	✓	✓	✓	✓
Reduced CO2 Emissions	✓	✓	✓				✓	✓			✓	
Reduce Thermal Stress	✓	✓	✓		✓		✓	✓	✓	✓		✓
Improved Aesthetic Appearance	✓	✓	✓		✓			✓	✓		✓	
Protect Biodiversity	✓	✓	✓		✓			✓	✓		✓	
Reduce Climate Impact	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓
Enhance the Human Condition	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓
Material Recycling	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
Innovative Design Solutions	✓		✓		✓	✓	✓	✓	✓	✓	✓	✓

[A] (Oguntona & Aigbavboa, 2023) [B] (Bayhan & Karaca, 2019) [C] (AlAli et al., 2023) [D] (Zari & Hecht, 2020) [E] (Jamei & Vrcelj, 2021) [F] (Beermann & Chen Austin, 2021) [G] (Du Plessis et al., 2021) [H] (Verbrugghe et al., 2023) [I] (Chayaamor-Heil, 2023) [J] (Ahamed et al., 2022) [K] (Dixit & Stefańska, 2023) [L] (Othmani et al., 2022)

According to Table 1, the expanding realm of biomimicry as a concept in sustainability has garnered worldwide attention and demand to harness the multitude of advantages presented by the natural world (Oguntona & Aigbavboa, 2023). Subsequently, Biomimicry arises as a viable biological approach that plays a role in the creation of eco-friendly constructed spaces (Aboulnaga & Helmy, 2022). The consumption of embodied and operational energy within the Construction Industry has been recognised as a key factor contributing to the ongoing increase in the atmospheric Carbon footprint (Lawrence, 2015). Therefore, Chayaamor-Heil (2023) has illustrated that Biomimicry is one of the best solutions to reduce energy consumption especially, in urban buildings.

3.2 CHALLENGES IN ADOPTING BIOMIMICRY FEATURES

Even though Biomimicry has numerous benefits especially in terms of energy efficiency and climate change mitigation due to rapid urbanisation, there are several challenges in adopting these strategies in the building construction industry (Chen Austin et al., 2020).

The following table illustrates some major barriers to implementing Biomimicry in the urban built environment.

Table 2: Challenges in adopting biomimicry features in the urban built environment

Benefits of Biomimicry	**Authors**											
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
Poor knowledge and awareness	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓
High initial cost	✓		✓	✓		✓		✓		✓		✓
Poor policies and regulations	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓
Interdisciplinary Collaboration		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
Research and Development	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Technological Limitations			✓		✓	✓			✓	✓	✓	✓
Time consumption	✓	✓	✓		✓	✓	✓	✓		✓		✓
Attitude of the people	✓	✓	✓	✓	✓		✓	✓	✓		✓	
Unavailability of material and technology	✓		✓	✓		✓	✓	✓	✓	✓	✓	✓
Scalability	✓		✓	✓	✓	✓		✓	✓		✓	

[A] (Dixit & Stefańska, 2023) [B] (Jamei & Vrcelj, 2021) [C] (Nkandu & Alibaba, 2018) [D] (Pawlyn, 2019) [E] (Othmani et al., 2022) [F] (Sodiq et al., 2019) [G] (Ferwati et al., 2019) [H] (Aboulnaga & Helmy, 2022) [I] (AlAli et al., 2023) [K] (Viholainen et al., 2016) [L] (Chen Austin et al., 2020)

As per Table 2, higher initial costs and investments in advanced materials and technologies can be prohibitive, despite the long-term savings and efficiencies offered (Dicks et al., 2021). Additionally, a lack of awareness and understanding among stakeholders, including architects, engineers, and planners, hampers widespread implementation (Zari & Hecht, 2020). The complexity of integrating biomimetic features requires a multidisciplinary approach and extensive collaboration, which can be difficult to coordinate (MacKinnon et al., 2022). Furthermore, there are challenges in measuring the sustainability impact of biomimetic designs due to the lack of standardised metrics (MacKinnon et al., 2022). Overcoming these barriers necessitates increased education, training, and a shift in industry practices to fully realise the potential of biomimicry in sustainable urban design (Pawlyn, 2019).

4. BIOMIMICRY IN URBAN DESIGN

In urban and architectural design, biomimetic concepts can be applied to tackle global environmental issues (Zari, 2018). Architecture in modern cities requires a tremendous amount of energy for construction, maintenance, and operation, directly and indirectly causing global environmental issues, such as loss of biodiversity or climate change through greenhouse gas emissions (Grimm et al., 2008). It has been proposed that the biomimetic approach can address these challenges at multiple scales, from single mechanical units (materials) to buildings, up to entire urban areas (Aboulnaga & Helmy, 2022). Biomimicry offers an opportunity to operationalise sustainability and regenerative development on architectural and urban projects (Hes & Du Plessis, 2014; Zari, 2018). The practice of biomimetic architecture faced the first increase throughout the nineties, within the beginning of a global context of the energy transition, giving birth to iconic biomimetic projects such as the Eastgate building, (1996) (Chayaamor-Heil, 2023). According to Zari (2017, 2018) analysing the urban built environment from the perspective of how ecosystems function, and then designing changes to cities, buildings, and building components so that they begin to quantifiably emulate the functions of ecosystems could work towards the creation of cities where positive integration with, and restoration of local ecosystem services could be realised. Mimicking biological morphology is one of many conventional applications of biomimetics in the field of architecture, and the subjects of this mimicry are not exclusively single organisms or organisms per se, but also the products of their biological behaviour, such as nests (Fujii et al., 2016; Uchiyama et al., 2020). Currently, the focus is less on aesthetics and more on mimicking functional aspects of living systems. As a measure to reduce the environmental impacts of buildings, the biomimetic approach provides design elements that, for example, collaborate with the economics of materials and the optimisation of lighting and heating (Buck, 2017). Therefore, it is believed that using biomimicry in architectural design will result in more ecological buildings that will be easier to update in the future while using less energy and spending less money on maintenance (Pradhan & Choudhury, 2023; Suresh Kumar et al., 2020). Having discussed the concept of Biomimicry, the below section discusses a few examples of buildings that have used the Biomimicry concept and the benefits gained due to their incorporation.

4.1 BIOMIMICRY INCORPORATED BUILDING PROJECTS

Eden Project, Cornwall

The Eden Project, situated in a reclaimed kaolinite mine, stands as the largest greenhouse plant globally. As mining activities continued during the design phase, the project necessitated a structure adaptable to fluctuating ground levels (Nkandu & Alibaba, 2018). The outcome is an array of dome structures resembling bubbles of different sizes scattered across the landscape. Inspired by nature, engineers opted for geodesic shapes, employing hexagons and pentagons, to create spherical surfaces effectively (Beermann & Chen Austin, 2021).

Figure 1: Eden project

Sinosteel International Plaza

The objective of this building was to create a lightweight structure that minimises material usage while effectively managing heat and maximising natural light (Mohamed et al., 2019). The solution for the building's design involved incorporating the optimal hexagonal honeycomb structure into the window system (Holstov et al., 2022). By analysing the various airflows and solar orientations across the site, the honeycomb building design ensures energy efficiency. This approach has resulted in an impressive energy efficiency rate of 75% (Chen et al., 2015).

Figure 2: Sinosteel International Plaza

East Gate Center, Harare

The Eastgate Centre, predominantly constructed from concrete, features a ventilation system inspired by termite mounds (Garcia-Holguera et al., 2016). This innovative approach has resulted in a remarkable 100% reduction in energy consumption for HVAC systems. Additionally, the building design facilitates natural ventilation and lighting, further enhancing its energy efficiency (Attia et al., 2022).

Figure 3: East Gate Center, Harare

Council House, Melbourne

CH2 employs a ventilation strategy inspired by termite mounds, utilising natural convection, ventilation stacks, thermal mass, phase change materials, and water for cooling (Beermann & Chen Austin, 2021). The building's façade is designed with dermis and epidermis layers to create a microclimate (Bayhan & Karaca, 2019). Ventilation stacks are incorporated on both the north and south facades (Radwan & Osama, 2016). The ceilings feature a wavy shape to maximise surface area and enhance thermal mass capacity (Singh, 2020). Additionally, the west façade is equipped with timber louvres to optimise natural light penetration and views (Ahamed et al., 2022). The epidermis serves as the primary mechanism for sun and glare control while establishing a semi-closed microenvironment. Moreover, the presence of shower towers results in a temperature reduction of four to 13 degrees Celsius from the top of the tower to the bottom (AlAli et al., 2023).

Figure 4: Council House, Melbourne

Coral Reef Project Haiti

The self-sufficient energy village is designed to accommodate refugees from humanitarian disasters using standardised and prefabricated parts. This innovative project features two duplex passive residences interconnected by a transversal horizontal circulation, creating a cohesive living structure that can house over a thousand Haitian families (Achal et al., 2016). Each residence's roof serves as an organic suspended garden, promoting self-sufficiency by allowing families to cultivate their food and recycle waste. Additionally, the design fosters a thriving tropical ecosystem for local fauna and flora. The project is eco-designed, incorporating bioclimatic systems and renewable energy sources to ensure sustainability and resilience (Elshapasy et al., 2022).

Figure 5: Coral Reef Project Haiti

City Hall, London

Designed by Norman Foster, this building emulates a cut sphere to reduce the surface area exposed to direct sunlight, allowing for passive energy savings. The form minimises wind resistance, contributing to the building's energy efficiency (Nkandu & Alibaba, 2018).

Figure 6: City Hall, London

Biomimicry has been successfully employed in numerous projects, yielding significant benefits, particularly in energy efficiency. This paper underscores the importance of transferring ideas from nature to engineering by comprehending fundamental concepts such as composition, behaviour, and ecology. It emphasises the necessity of differentiating between levels of biomimicry in architectural design, which range from organism-level information to ecosystem-level behaviour. These examples consist of various building typologies, the influence of natural systems, the application of architectural design principles, and problem-solving through diverse design solutions. Accordingly, the paper compares case studies and their objectives to extract key considerations for designing biomimetic urban building projects.

5. CONCLUSIONS

Biomimetic approaches in urban building construction and climate change mitigation leverage nature-inspired solutions to address environmental challenges. Biomimicry can reduce the urban heat island effect, lower CO_2 emissions, and enhance building energy efficiency by mimicking natural processes and systems. This study highlights the potential of biomimicry for innovative and sustainable urban design, emphasising its role in climate regulation, ventilation, and energy management. Despite its promise, widespread adoption faces obstacles such as limited awareness among stakeholders. Promoting education, training, and interdisciplinary collaboration is essential for integrating biomimicry into sustainable practices. Future research should focus on conducting empirical studies and developing pilot projects to validate the efficacy of biomimetic approaches. These studies can provide concrete evidence of the benefits and feasibility of biomimicry, encouraging broader adoption in the construction industry. Additionally, establishing policies and regulations that support and incentivise the use of biomimetic solutions can drive industry-wide changes towards sustainability.

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