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Article

Harnessing the power of biomimicry for sustainable innovation in construction industry

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Abstract: Biomimicry is increasingly being used to drive sustainable constructional development in recent years. By emulating the designs and processes of nature, biomimicry offers a wealth of opportunities to create innovative and environmentally friendly solutions. Biomimicry in industrial development: versatile applications, advantages in construction. The text emphasizes the contribution of bio-mimetic technologies to sustainability and resilience in structural design, material selection, energy efficiency, and sensor technology. Aside from addressing technical constraints and ethical concerns, we address challenges and limitations associated with adopting biomimicry. A quantitative research approach is implemented, and respondents from the construction industry rank biomimicry principles as the optimal approach to enhance sustainability in the industry. Demographic and descriptive analyses are underway. By working together, sharing knowledge, and innovating responsibly, we suggest approaches to tackle these obstacles and fully leverage the transformative power of biomimicry in promoting sustainable construction industry practices. In an evolving global environment, biomimicry reduces environmental impact and enhances efficiency, resilience, and competitiveness in construction industries.

Keywords: biomimicry; construction industry; industrial development; nature-inspired design; environ-mental sustainability

1. Introduction

The increasing environmental challenges and technological advancements have led to a growing need for sustainable development. In response, the construction industry increasingly turns to biomimicry, a discipline that draws inspiration from nature to inform design and innovation processes. This paper explores how biomimicry can drive sustainable development in construction by examining its applications, challenges, and prospects. Biomimicry is one of the most promising frontiers in sustainable innovation. It is a practice that draws inspiration from nature's designs, processes, and systems to solve human challenges. This approach fosters creativity and promotes ecological balance and efficiency in product design and industrial development. The construction industry is known to significantly impact the environment, with factors like energy consumption, waste generation, and resource depletion being significant concerns.

However, there is a growing interest in using biomimicry concepts to address these challenges and create more sustainable solutions. Biomimicry involves studying nature's designs, processes, and systems and using them as inspiration to solve human problems. In the construction industry, biomimicry can be applied in materials, design, and building systems to create more efficient, resilient, and eco-friendly structures. Nature-inspired construction can minimize environmental impact and establish sustainability. The construction industry is known to significantly impact the environment, with factors like energy consumption, waste generation, and resource depletion being significant concerns.

Biomimicry raises ethical considerations related to the appropriation of biological designs and processes. It is essential to approach biomimetic design and development with respect for nature, indigenous knowledge, and cultural diversity, ensuring responsible innovation practices. Biomimicry mimics nature to develop sustainable innovations worldwide. It promotes resource efficiency, waste reduction, and biodiversity conservation. In the context of sustainability, imitating nature has proven its superior ability to solve problems faced by humanity in practical ways that have led to the preservation of the Earth's resources and reduced waste and unsustainable energy consumption. The construction industry can adopt biomimicry strategies to reduce global warming despite cement production being the primary material. By harnessing the power of biomimicry, construction industries can drive sustainable practices that prioritize resource efficiency, environmental stewardship, and resilience.

Biomimicry technology, which involves emulating nature's models, systems, and elements to solve human problems, is an innovative approach gaining significant traction in various fields, including the modern construction industry. This technology leverages nature's time-tested patterns and strategies to create sustainable and efficient solutions. The concept of learning from nature dates back to ancient times, but the term "biomimicry" was popularized by Janine Benyus in her 1997 book "Biomimicry: Innovation Inspired by Nature". Early examples include Leonardo da Vinci's studies of bird flight, which influenced his designs for flying machines. Increased academic and industrial research, with universities offering dedicated programs and courses in biomimicry. Materials science, robotics, and computer modelling advancements have enabled more precise replication of natural structures and functions. Formation of organizations such as the Biomimicry Institute and Biomimicry 3.8, promoting interdisciplinary collaboration and innovation.

Importance of biomimicry in the modern construction industry:

Sustainability:

Energy Efficiency: Buildings designed using biomimicry can significantly reduce energy consumption. For example, the Eastgate Centre in Zimbabwe uses principles from termite mounds to maintain comfortable temperatures with minimal energy use.

Resource Management: Biomimetic designs often utilize resources more efficiently, reducing waste and promoting renewable materials.

Resilience and adaptability:

Climate Adaptation: Structures inspired by nature can better withstand environmental challenges, such as buildings designed to mimic the aerodynamic forms of birds to resist strong winds.

Self-Healing Materials: The development of materials that can repair themselves, inspired by biological processes, leads to longer-lasting infrastructure.

Innovation and performance:

Structural Efficiency: Nature-inspired designs, like the Eiffel Tower's resemblance to the femur bone, offer high strength-to-weight ratios, allowing for lighter and more robust structures.

Water Management: Biomimetic water harvesting and management solutions, such as the Namib Desert beetle-inspired water collection surfaces, address water scarcity issues in urban areas.

Economic benefits:

Cost Savings: Energy-efficient buildings reduce operational costs. For instance, bio-inspired cooling systems can lower air conditioning expenses.

Market Differentiation: Adoption of innovative and sustainable building practices can enhance a company's competitive edge and attract eco-conscious consumers.

Biomimicry technology holds immense potential for revolutionizing the construction industry by promoting sustainability, resilience, and innovation. By emulating nature's genius, modern construction can achieve new heights of efficiency and harmony with the environment, addressing contemporary challenges and paving the way for a sustainable future.

The research philosophy underlying this study is a combination of interpretivism and pragmatism. Interpretivism allows for an in-depth understanding of participants' perspectives, while pragmatism facilitates the practical application of research findings. Multiple data sources were analyzed using a mixed-methods research approach, which involved triangulating the information obtained. The research design encompassed a literature review and a survey targeting construction professionals. This de-sign enabled the exploration of existing research, the assessment of industry awareness and application of biomimicry concepts, and the examination of successful biomimetic applications in construction. The research strategy involved a sequential explanatory strategy, starting with the literature review to establish foundational knowledge, then the survey to gather empirical data to validate and illustrate findings. Both qualitative and quantitative data were collected. Qualitative data included insights from literature sources and survey responses. Quantitative data comprised numerical data from survey responses for statistical analysis.

2. Literature review

Biomimicry applies natural solutions to design challenges in architecture and urban planning and is widely recognized. For its potential to enhance sustainability. (Adekunye and Oke, 2022; Austin et al., 2020). Some consider it crucial to architecture for sustainable building designs (Baumgartner, 2013; Bitar et al., 2022). Bio-mimetic architecture mimics natural forms, processes, and ecosystems to create innovative and sustainable designs (Blanco et al., 2021). The use of biomimetic principles in architecture extends to urban design, where biomimetics has been applied across different scales, from materials to larger urban contexts (Buck, 2016) and various stages of construction, including early construction, finishing, foundation, frame stages, and project planning. The approach demonstrates its versatility and highlights its potential impact (Butt, 2022; Chairiyah, 2023). The objective is to develop sustainable and efficient designs, taking inspiration from nature (Chayaamor-Heil, 2018).

By mimicking biological strategies and processes, Biomimicry offers innovative solutions to optimize building systems and address issues such as urban heat island effects and energy consumption (Dyck et al., 2019). Studies have shown that it promotes sustainable construction practices and inspires climate-responsive designs, contributing to efficient and sustainable built environments (Elsakksa and Marouf, 2022; Ergün and Aykal, 2022; Fok et al., 2022). Architects are increasingly turning to Biomimicry to minimize adverse environmental impacts and drive innovation in the construction industry (Franzini et al., 2018; Han et al., 2015). By leveraging nature-inspired solutions, Biomimicry offers an efficient pathway to address climate-related energy challenges and enhance architectural sustainability (Imani and Vale, 2022; Jamei and Vrcelj, 2021). Furthermore, Biomimicry can contribute to disruptive and sustainable outcomes in the construction industry by enhancing technology readiness, leadership competence, and knowledge (Khoja and Waheeb, 2020).

However, the application of Biomimicry varies across different regions and environments (Klemm and Almeida, 2018). Research has shown its potential in optimizing building thermal performance, mitigating urban heat island effects, enhancing user comfort, and increasing office and building productivity, particularly in hot climate countries like Nigeria (Matinaro and Liu, 2017). Additionally, Biomimicry has been recognized as a valuable approach for energy-efficient building skin design, showcasing its potential to contribute to reducing energy consumption in the built environment (Mirniazmandan and Rahimianzarif, 2017; Oguntona and Aigbavboa, 2017; Webb, 2021)) and considerably reducing the building’s carbon footprint (Oguntona and Aigbavboa, 2018). Successful implementations have demonstrated its ability to improve building systems while considering the unique environmental contexts of specific regions (Oguntona and Aigbavboa, 2019; Oguntona and Aigbavboa, 2023). Moreover, integrating Biomimicry with established sustainability frameworks like BREEAM can offer comprehensive approaches to sustainable architecture (Pacheco-Torgal, 2014). BREEAM, which stands for Building Research Establishment Environmental Assessment Method, is a way to measure how environmentally friendly a building is. It was created by the Building Research Establishment in the UK. BREEAM looks at things like how a building is designed, built, and run to see how well it's doing at being kind to the environment.

As we move towards a more sustainable future, the construction industry is leading the way by focusing on biomimetic materials that benefit the environment and create beautiful and functional structures. Biomimetic materials mimic natural processes and structures in living organisms to create innovative and sustainable construction solutions (Radwan and Osama, 2016; Rosario et al., 2023). Incorporating biomimetic materials can develop lignocellulose materials with excellent mechanical properties and environmental stability (Uchiyama et al., 2020; Verbrugghe et al., 2023).

Despite its potential, there remains a gap in biomimicry research and applications in regions such as the UAE. While Biomimicry holds promise for sustainable innovation in the construction industry, some barriers need to be addressed, including adoption, lack of knowledge, challenges, and the need for a culture change (Zari and Hecht, 2020). Organizational culture significantly influences the success of sustainability initiatives within businesses. It implies that a company’s culture can either support or hinder its efforts towards sustainability. Matinaro and Liu (2017) conducted a case study on a Finnish construction business, highlighting the significance of organizational culture in driving sustainability. They emphasized the importance of organizational culture in contributing to sector-level transitions towards sustainability. This supports the claim by Franzini et al. (2018) that organizational culture plays a crucial role in influencing sustainability outcomes. Firms' sustainability beliefs and practices vary depending on differences in organizational culture's values and norms.

Moreover, building sustainability within organizations involves recognizing it as an organizational issue that requires a focus on values, beliefs, and employee behaviors inherent in organizational culture. Baumgartner (2013) supports this notion, proposing a conceptual framework for managing corporate sustainability. Additionally, the literature suggests that a sustainability-supportive and innovative organizational culture facilitates adopting green practices to enhance sustainability performance (Fok et al., 2022).

Overcoming barriers to applying biomimicry in the construction industry requires a comprehensive approach focused on education, research, economic incentives, regulatory support, and interdisciplinary collaboration. Educating professionals and integrating biomimicry into academic curricula will build foundational knowledge, while increased funding and collaborative research can drive innovation. Economic incentives and detailed cost-benefit analyses can demonstrate the long-term advantages of biomimetic designs, making them more appealing to developers. Advocacy for supportive regulations and the development of certification programs will help standardize and legitimize biomimetic practices. Finally, fostering interdisciplinary teams and leveraging advanced digital tools will ensure that biomimetic principles are effectively and efficiently incorporated into construction projects, leading to more sustainable and innovative buildings.

Biomimicry benefits and applications must be embedded in the organizational culture to ensure success. In this context, the paper's goal is to assess the organizational culture regarding the application of Biomimicry in the UAE construction industry. By overcoming the organizational culture barrier, the UAE construction industry can harness the potential of Biomimicry to achieve sustainable practices and address environmental challenges.

3. Biomimicry framework

By observing and emulating nature's time-tested strategies, biomimicry offers a framework for creating innovative, efficient, and sustainable solutions across various industries. Here are some of its applications:

1) Structural Design Inspired by Nature: Nature's structural designs, such as the honeycomb structure of beehives and the bone structure of birds, inspire innovative architectural and engineering solutions. Industries can create lightweight, durable, and resource-efficient structures by mimicking these natural designs.
2) Material Selection and Properties: Biomimicry informs the selection and properties of materials used in industrial processes. Bio-inspired materials, such as self-healing polymers and biodegradable plastics, offer sustainable alternatives to traditional materials, reducing environmental impact and promoting circularity.

3) Energy Efficiency and Optimization: Nature has evolved highly efficient energy systems and processes, such as photosynthesis and animal locomotion. By mimicking these biological processes, industries can optimize energy use, reduce waste, and enhance overall efficiency in manufacturing and production processes.
4) Biomimetic Sensors and Actuators: Biomimicry inspires the development of sensors and actuators that mimic biological systems for sensing and responding to environmental stimuli. These biomimetic devices offer enhanced sensitivity, responsive-ness, and adaptability for various industrial applications, from robotics to environmental monitoring.

Despite its potential benefits, biomimicry adoption faces challenges due to a need for widespread understanding and awareness among industry stakeholders. Education and outreach efforts are needed to promote greater awareness and appreciation of biomimicry principles. Biomimetic designs may encounter technical and engineering constraints, such as scalability, manufacturability, and compatibility with existing technologies. Interdisciplinary collaboration and research are essential to address these challenges and optimize biomimetic solutions for industrial applications.

The analysis of quantitative data included establishing an electronic questionnaire via the Microsoft Form program, which contains a mechanism for collecting and analyzing data automatically and providing graphs and statistical data that contribute to the data analysis process.

The four critical stages in the Biomimicry Thinking/Design framework are:

1) DISCOVER: Discover the strategies and mechanisms.
2) EXPLORE: Explore the functions and the context.
3) CREATE: Create designs inspired by the organism.
4) EVALUATE: Evaluate the design using Life's Principles.

Implementing biomimicry methodology in construction involves several vital steps to ensure the effective integration of nature-inspired designs. The process begins with defining specific construction challenges and analyzing the site context, then researching and selecting biological models that solve similar problems. The next step is to abstract functional principles from these models and translate them into design guidelines, followed by collaborative ideation, detailed design development, and prototyping to validate concepts. Performance testing and environmental assessments ensure the designs meet functional and sustainability criteria, leading to iterative refinements. Finally, detailed construction planning and execution and post-construction monitoring and evaluation ensure the project aligns with biomimetic principles, resulting in innovative, sustainable buildings. Documentation and knowledge sharing throughout the process help advance the field of biomimetic construction.

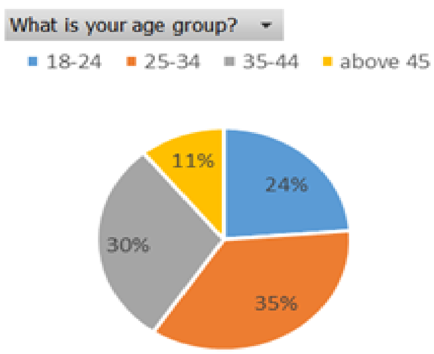
Several technical challenges are faced, such as accurately translating biological principles into practical design solutions and the need for advanced materials that can replicate natural properties. The lack of standardized methods for integrating biomimicry into construction processes can hinder consistency and scalability. Additionally, current construction technologies and tools may not be fully equipped to handle the sophisticated modeling and testing required for biomimetic designs. Ensuring that biomimetic structures meet existing building codes and performance standards adds another layer of complexity, requiring rigorous testing and validation to prove their reliability and efficacy in real-world applications.

4. Results

4.1. Demographic analysis

This study employed a quantitative research approach with confidence which aims to gather information from respondents. To present informative evidence on the respondents' perspectives on biomimicry principles as an evaluation index of sustainability, the study utilized questionnaire survey. The study's respondents were chosen randomly from a list of registered industry professionals (including Engineers, quantity control managers, R&D managers, Design engineers, project managers, and others) and biomimicry specialists in the industries. Structured questionnaires, consisting of closed-ended questions, were administered to the respondents.

Demographic analysis involves examining characteristics such as women's age and years of experience. This analysis revealed the number of participants in each age group. More than 100 people participated in this survey, and the majority of the 35% of participants fell within the 25–34 and 35–44 age groups. The questions listed below are part of the respondents' survey questionnaire. A few of them excluded specific questions. Hence, the number of respondents who answered that particular question is provided as 60. However, the majority of them answered only some of the questions. Only 60 participants answered all the questions. This analysis revealed the job role of the survey participants. 25% were Architect, 19% were civil engineers, 14% were Project managers, and finally, 42% of participants answered that they are working in other roles within the construction industry (**Figure 1a–c**). The demographic background of the respondents revealed that 63.8% are male while 36.2% are female. The majority of the respondents possess a master's degree (25%), followed by a bachelor's degree (65%) and a diploma (12%). **Table 1** shows the mean ranking of each biomimicry principle, providing a clearer picture of the consensus reached by respondents.



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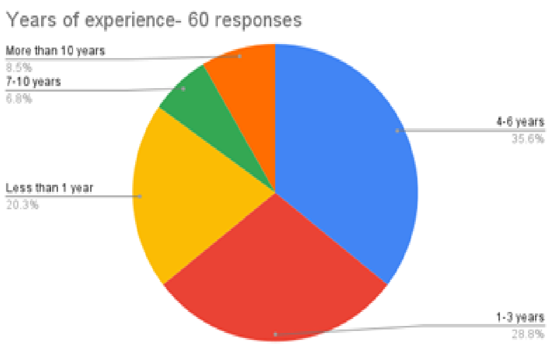

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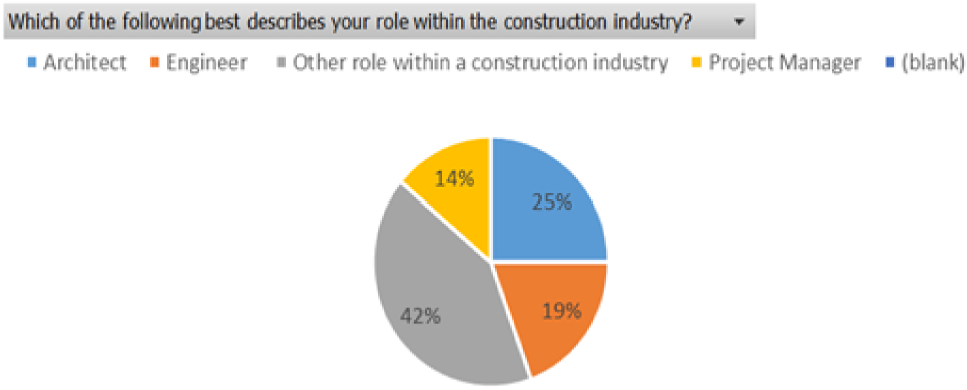

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Figure 1. Demographic analysis: **(a)** age group; **(b)** years of experience; **(c)** role within the construction industry.

Table 1. Respondents rate biomimicry principles in optimizing sustainability in the construction industry.

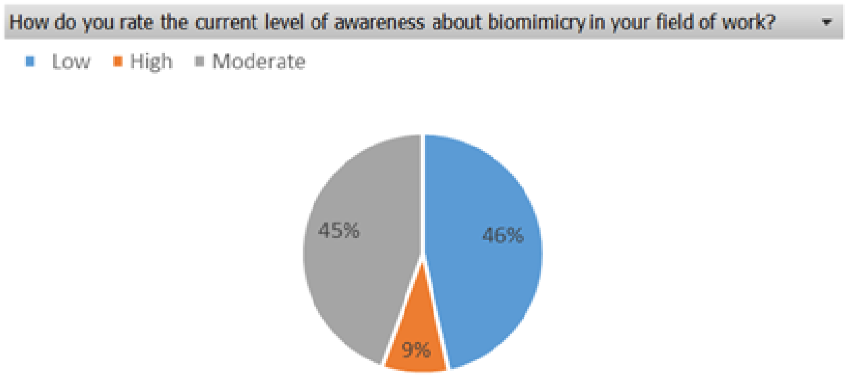
	Mean ($\bar{x}$)	**Standard deviation (σX)**	**Rank (R)**
Biomimicry processes mimic natural cycles to improve sustainability	4.62	0.66	1
In terms of resilience and adaptability, does biomimetic designs outperform traditional designs?	4.491	0.522	2
Biomimicry has a greater potential for cost savings in the long run.	4.43	0.57	3
The current level of awareness about biomimicry in product design field of work	4.32	0.755	4
Receptiveness in the product design industry for adopting biomimicry practices	4.24	0.731	5
The extent to prioritize using readily available biomimicry principles	4.17	0.853	6
Harnessing freely available energy sources for biomimicry	4.08	0.809	7
By considering innovation in product design, do human creativity alone is sufficient?	3.92	1.121	8
Significance of interdisciplinary collaboration and knowledge sharing in implementing biomimicry principles.	3.91	1.1	9
The most effective way to increase awareness about biomimicry among students and professionals	3.87	1.005	10
Using multi-functional design	3.601	1.0	11
Breaking down products into benign constituents	3.65	1.031	12

The aim was to elicit their perceived likelihood of the adopted biomimicry principles to optimize sustainability based on a five-point Likert rating scale (extremely likely = 5, likely = 4, neutral = 3, unlikely = 2, and extremely unlikely = 1). Sixty completed questionnaires were received, representing a 60% response rate. The data was analyzed using SPSS, which employed descriptive statistics. This study used a quantitative research approach to evaluate biomimicry principles as an evaluation index of sustainability. The data was analyzed using SPSS, and factors with a mean score of 2.40 or more were considered significant. The study compared the mean values and standard deviation of the significant factors.

From the results obtained, 'Biomimicry processes mimic natural cycles to improve sustainability' ranked first with a mean score of 4.62 and standard deviation (SD) of 0.66, which the respondents considered as the most critical biomimicry principle that can promote sustainable product design practices. 'In terms of resilience and adaptability, does biomimetic designs outperform traditional designs?' was ranked second with a mean score of 4.491 and SD of 0.522; 'Biomimicry has a greater potential for cost savings in the long run' was ranked third with a mean score of 4.43 and SD of 0.57. As the factor with the highest mean ranking, biomimicry processes mimic natural cycles to improve sustainability at the different stages of product design. This is a crucial sustainability factor within the construction industry.

4.2. Descriptive analysis

BREEAM 2 depicts the sample of descriptive analysis. The data indicates that approximately 91% of respondents perceive the current level of awareness about biomimicry in their respective fields as low to moderate, with only 9% reporting high awareness (**Figure 2a**). Analysis reveals that 21% to 28% of participants consistently practice corporate recycling for construction materials (**Figure 2b**). Additionally, 27% of respondents believe that the construction industry is somewhat receptive to biomimicry, while 45% remain neutral, and 27% perceive the industry as resistant or somewhat resistant (**Figure 2c**). Furthermore, when asked about the importance of designing structures to minimize material waste and optimize efficiency, most respondents (68%) indicated that it is essential (ranging from 4 to 5 on the scale) (**Figure 2d**).



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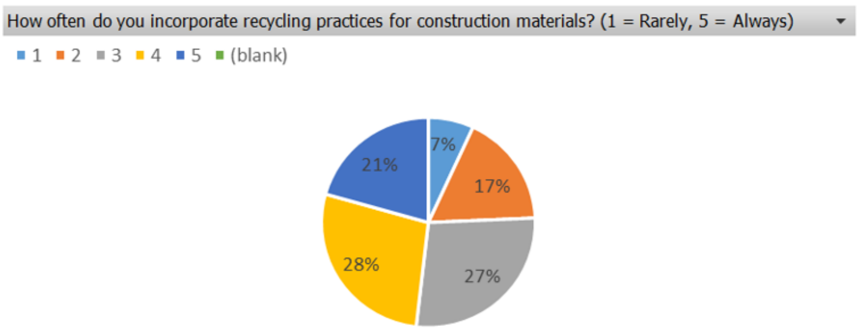

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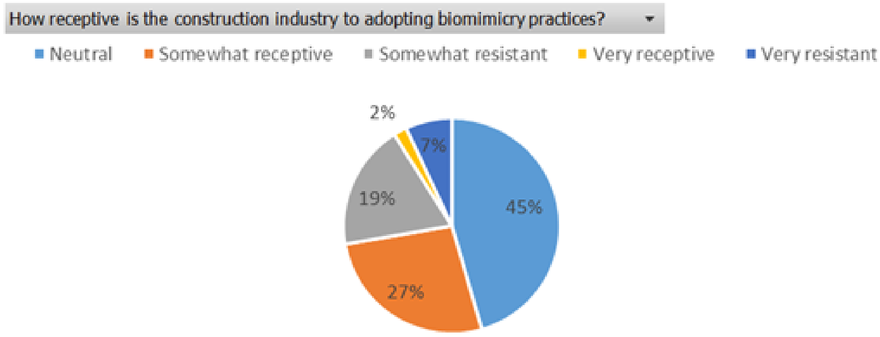

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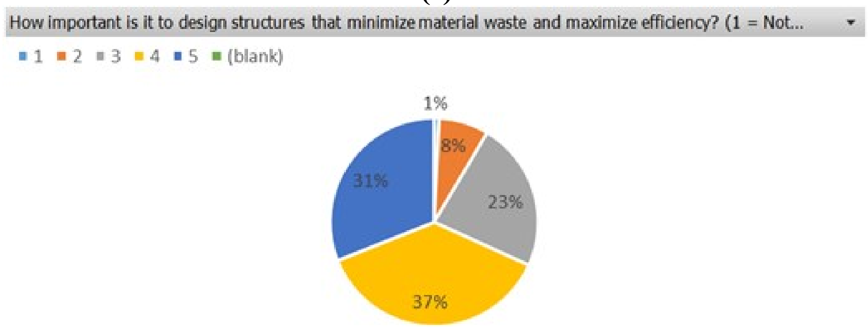

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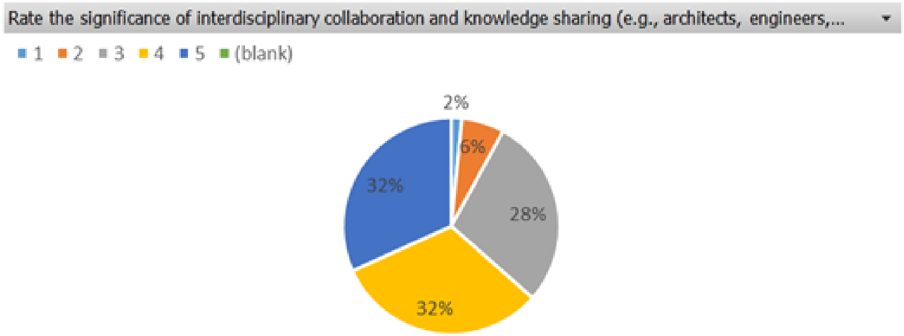

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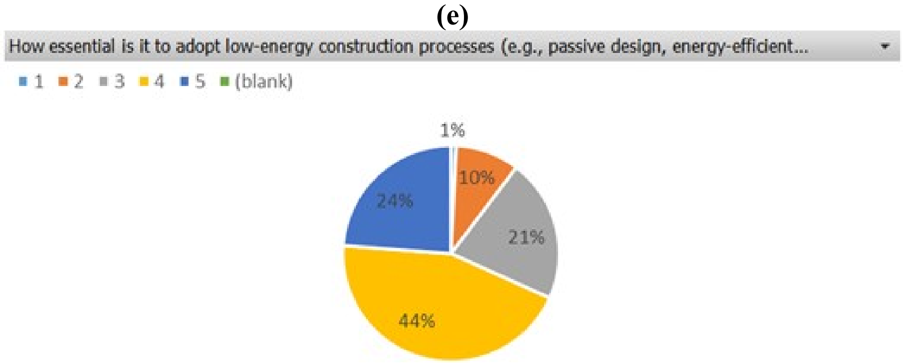

(f)

Figure 2. Descriptive analysis: **(a)** awareness about biomimicry; **(b)** recycling practices of construction materials; **(c)** receptive to adopt biomimicry practices; **(d)** to minimize material waste and maximize efficiency; **(e)** interdisciplinary collaboration and knowledge sharing; **(f)** adopt low-energy construction process.

The rating scale demonstrates the importance of interdisciplinary collaboration and knowledge sharing (e.g., architects, engineers, biologists) in implementing biomimicry principles. The ratings range from one to five and are as follows: Not Significant: 2%, Slightly Significant:6%, Moderately Significant: 28%, Significant:

32%, Highly Significant: 32% (**Figure 2e**). **Figure 2f** shows how essential it is to adopt low-energy construction processes (e.g., passive design, energy-efficient materials). The responses indicate a balanced distribution, between 21% of (3 = Moderately Essential) and 24% of (5 = Extremely Essential), with a notable 10% of respondents selecting that adopt low-energy construction processes as just Slightly Essential (2). However, 44% of the respondents Agreed it would be Essential (4) to adopt low-energy construction processes, suggesting generally positive opinions towards adopting low-energy construction processes.

5. Conclusion

Biomimicry has immense potential for driving sustainable development in the development of the sustainable construction industry by drawing inspiration from nature's designs and processes. This study highlights biomimicry's potential for sustainable solutions in construction and design, emphasizing its role in creating innovative materials and technologies. Knowledge gaps among architecture and engineering stakeholders hinder biomimicry's adoption despite its benefits. The critical sustainability criterion revolves around efficient energy and material use. Sustainable construction materials and technologies should prioritize reusability, recyclability, low greenhouse gas emissions, durability, local production, and longevity. These factors are essential for enhancing sustainability in construction projects. Structural engineers favor uniform materials and simple shapes over nature-inspired, complex, adaptive forms. Only 44% of the respondents agreed that embracing low-energy construction methods is crucial, indicating generally favorable attitudes toward such practices. Addressing these challenges in future can lead to more sustainable and efficient designs in the built environment.

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Conflict of interest: The authors declare no conflict of interest.

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