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Review paper

BIOMIMETIC FORMS IN ARCHITECTURE: DEFINITION, APPLICATIONS AND CHALENGES

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Abstract

The implementation of biomimicry as a design approach in architecture is still in its early stages. Biomimicry is defined as a solution to design problems inspired by natural patterns and has a wide range of applications in architecture, from materials, form, to regenerative ecosystem level. The primary purpose of this paper is to investigate the development of biomimicry in architecture from the aspect of form, through a bibliometric review. In this study, articles published in the Web of Science database (2014–2024) were analyzed. VOSviewer software was used to conduct the bibliometric analysis and to represent the analysis results. In order to increase the knowledge of biomimicry, this study also analyzes how biomimetic forms can be applied in architecture and explores the various challenges in their implementation. The challenges of implementing biomimicry in architecture are grouped based on social and technological challenges. Emphasizing the importance of the need for biomimicry in the design of contemporary architectural forms is the goal of this study. Based on the results, future research directions and practical recommendations were presented to support the successful deployment of innovative design approach.

Key words: *Biomimicry (BM), Form, Architecture (AR), Bibliometric analysis*

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1. INTRODUCTION

In the last few decades with the application of digital technologies, progress has been achieved in the development process of architectural design. At the same time, new ideas and approaches began to emerge that provide architectural solutions based on forms from nature. Recognizing the qualities of such forms, architects have always strived to imitate nature. Architects and designers refer to nature-based design using interpretations of several bio-related keywords, such as biomimicry, biomimetics, bionics, biomorphism, ecomimicry and organic design [1]. Biomimicry is a promising emerging research field defined as a solution for design problems inspired by natural models, systems, and elements [2]. The term was coined by Janine M. Benyus in 1997 and is a junction of the Greek words 'bios', meaning 'life', and 'mimesis', meaning imitation [3]. In particular, 'biomimicry' stresses the interconnectedness of systems to solve complex problem in design and today's environmental challenge [4]. In the flora and fauna, it is possible to find a large number of geometric shapes and forms that have developed in response to the limited resources of the environment. Biomimicry offers completely new ways of approaching design so that the whole system can be optimized and a radical increase in resource efficiency can be achieved.

Development processes and systems based on digital engineering, as well as on complex geometry and biological principles, are connected in contemporary architectural design. Digital tools, robotic prefabrication and additive manufacturing have enabled new progress in expanding the boundaries of the theory of architectural phenomenology, from the representation of space to the representation of systems.

Recent years have seen an increase in studies on digital design and state of the art manufacturing methods in biomimetic architecture. However, despite the increased interest in biomimetic research in architecture, the concept itself is still ambiguous for many practitioners and researchers.

When there is an increased level of interest in an emerging concept or technology, there may be a risk of increased confusion due to the fragmentation of the presented knowledge about this concept and its application. Bibliometric analysis play a vital role in bringing together previous studies' results. To answer specific research questions, a systematic literture review was used, ensuring the inclusion of only related literature, identifying what is known and unknown about the topic under study.

With the aim of contributing to the increased understanding of the role of design methodology and technology in biomimetic architecture, the current study uses the bibliometric analysis approach to answer the following research questions:

- How to transfer biomimetic morphological principles to architectural design?
- What are the potential and current applications of biomimetic forms in architecture?
- What are the main challenges facing the adoption of biomimicry in architecture from the social and technological perspective?

The structure of this study is as follows: after this section, Section 2 presents the research methodology, then Section 3 presents the literature characterization and bibliometric findings with visualization performed using VOSviewer. The findings are discussed in the same chapter. In Section 4 are presented the conclusions, limitations and implications of the study.

2. RESEARCH AND METHODOLOGY

The essential purpose of this paper is to survey publications and research directions in the field of biomimetic forms in architecture using the scientific literature database. Web of science is recognised as one of the databases with the most extensive data sources for a wide range of topics. To define the current trends, characteristics and potential applications of biomimetic forms related to architecture, the methodological approach of this study is a systematic literature review (SLR) [5]. There are three main phases in SLR research methodology, which are the identification, screening, and eligibility to decide what should be included in the review process. The following terms were used in the identification phase on Web of Science database: “biomimetics” OR “biomimicry” AND “architecture” OR “architectural design” AND “forms” AND “computational design” OR “robotic manufacturing”. The search included only scientific articles, conference papers and reviews written in English. The search result consists of 353 studies; among them, 35 were duplicated and removed. In the screening phase, the search was for studies that included defined terms in the title, abstract or keyword list, in order to ensure the use of studies directly related to the studied topic.

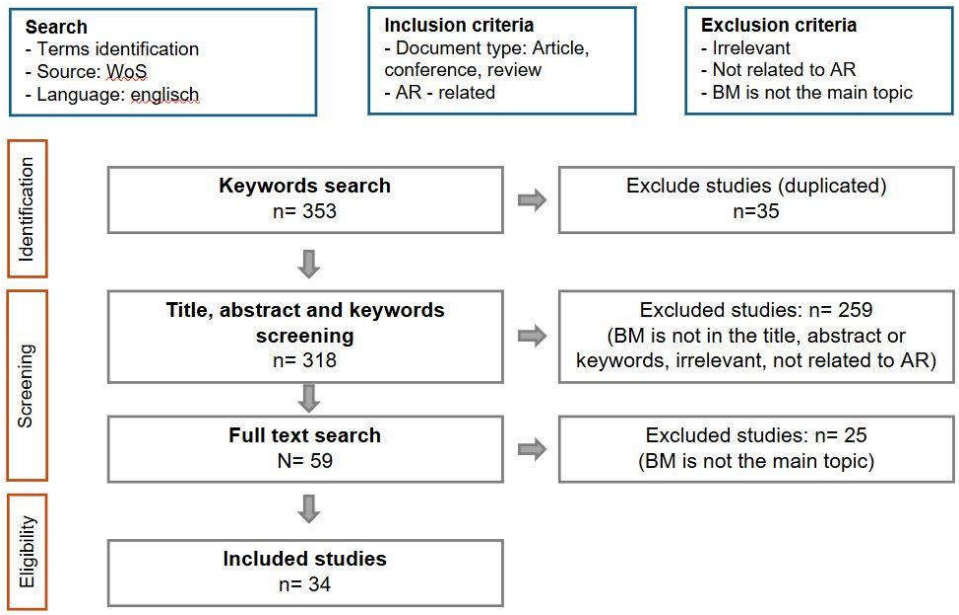

Figure 1. Methodological framework of the research

Studies that are irrelevant to biomimetic architecture from the aspect of form and computational design are excluded. In the continuation of the research, a full text search was performed. In this step studies not related to architectural form and computational design in biomimetic architecture were excluded (e.g. studies that mentioned computational design and robotics in biomimetic architecture as a future recommendation in the abstract). Accordingly, 34 studies were selected to be included in this study. Bibliographic data from the Web of Science database were analyzed in VOSviewer Software Tool. The latter allows the creation of a keyword network in which natural language algorithms and text mining methods are used to investigate the

relationships between the most repeated keywords about the studied topic, and then cluster them accordingly [6].

3. RESULTS AND DISCUSSION

Articles from the Web of Science database were studied to identify bibliometric indicators in the research, such as thematic classification, annual publication analysis, geographic area analysis, keyword co-occurrence, citation by source and authorship analysis.

3.1. Biomimetic form in relevant research areas

Figure 2 presents a diagram illustrating the thematic classification of biomimetic form in architecture. Based on the diagram, it can be concluded that in the field of Construction Building Technology, biomimetic form is the most researched topic with a number of papers of 122. It is important to highlight significant studies in fields such as Engineering (99), Materials Science (55), Architecture (34) and Energy Fuels (8).

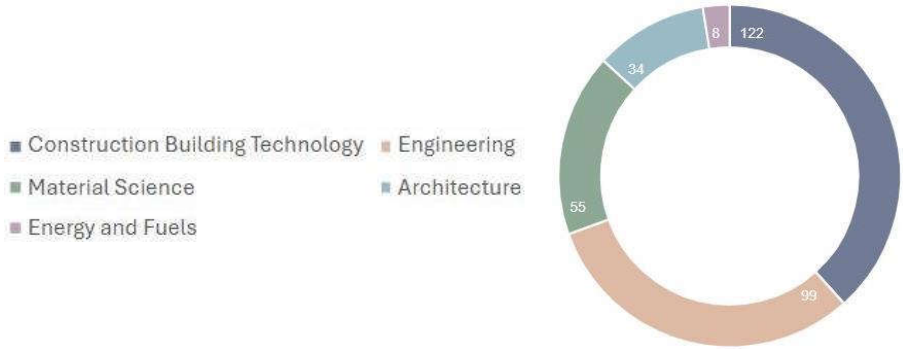

Figure 2. Subject area distribution of the related literature in biomimetic architectural forms

3.2. Anual publication analysis

Based on Figure 3, there is an evident increase in the number of published scientific papers and interest in the topic of biomimetic form in architecture. The chart covers the period from 2014 to 2024. The distribution of publications by year indicates the relevance of the topic and the need for designers and practitioners to turn to innovative approaches to support sustainability. This review included 34 papers related to studied topic. As of the date of this review (April 2025), the largest number of papers was published in 2022 (12 papers) and 2024 (10 papers). This very rapid increase in the number of studies each year may show some signs of awareness of the potential of biomimetic form in architecture and confirms the need to clearly explain the meaning of biomimicry and identify possible challenges for its application. The increased interest in biomimicry can also be seen in the number of papers that included case studies or pavilions.

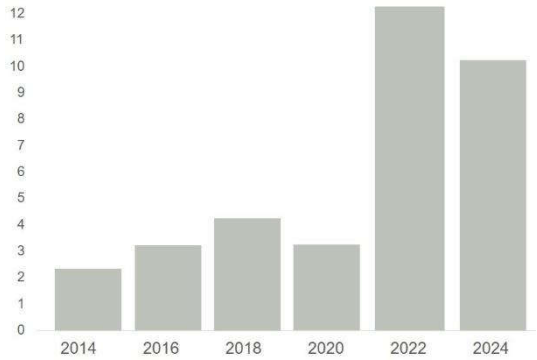

Figure 3. Annual number of publications related to biomimetic architectural forms

3.3. Geographical location

Figure 4 shows the results of the bibliometric analysis based on co-authorship using countries as the unit of analysis. The minimum number of documents in a country is set to 1. The results show that 12 countries meet the thresholds in the data inclusion phase, but only countries with more documents are selected for the co-author network. The results show that only 8 countries meet the thresholds. Figure 4 shows four clusters. Cluster 1, colored green, includes the United States, Germany, and India. Cluster 2 (red) includes China, Australia, Italy, and England. Finally, cluster 3 (blue) refers to the Netherlands, which is the only country in this cluster, but has links to at least 6 countries. The size of the bubbles shows that the United States and Germany have more documents on the topics analyzed in this study.

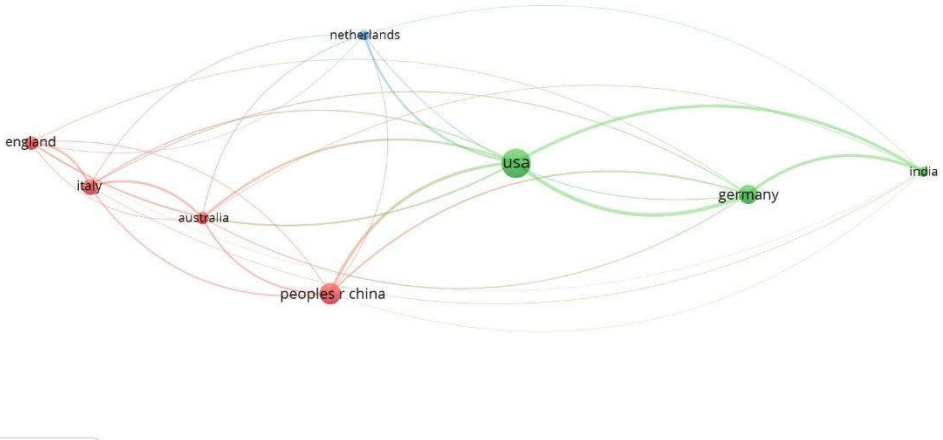

Figure 4. Network visualization of co-authorship by country. The size of nodes represents the frequency of occurrence, the lines between the nodes represents the co-occurrences of the co-authorship

3.4. Key word corelation – bibliometric analysis

To identify patterns of publications about biomimetic architectural forms and current trends in the international scientific literature, keyword co- occurrence was conducted using VOSviewer. The latter allows the creation of a keyword network in which natural language algorithms and text mining methods are used to investigate the relationships between the

most repeated keywords about the studied topic, and then cluster them accordingly [6]. Before conducting the co-occurrence analysis on VOS viewer, keywords with similar meanings were merged. Each map is characterized by nodes connected by the lines; the size of the bubbles indicates the frequency of occurrence or citations, while the lines represent the connection between the two concurrent keywords, creating a network map. The keywords analyzed were words that were repeated at least five times in the selected articles.

As a result, 44 keywords were obtained in 7 groups (clusters): biomimicry and sustainable construction (green), bio-inspired and computational design (red), building envelope performance (dark blue), sustainability and adaptation in architecture (light blue), design related to plant behavior and soft robots (purple), behavior and growth through model (yellow), biomimetics related to animals, actuators and movements (orange). This study found that the autors preferentialy used the keywords “Biomimetics” and “Biomimicry”.

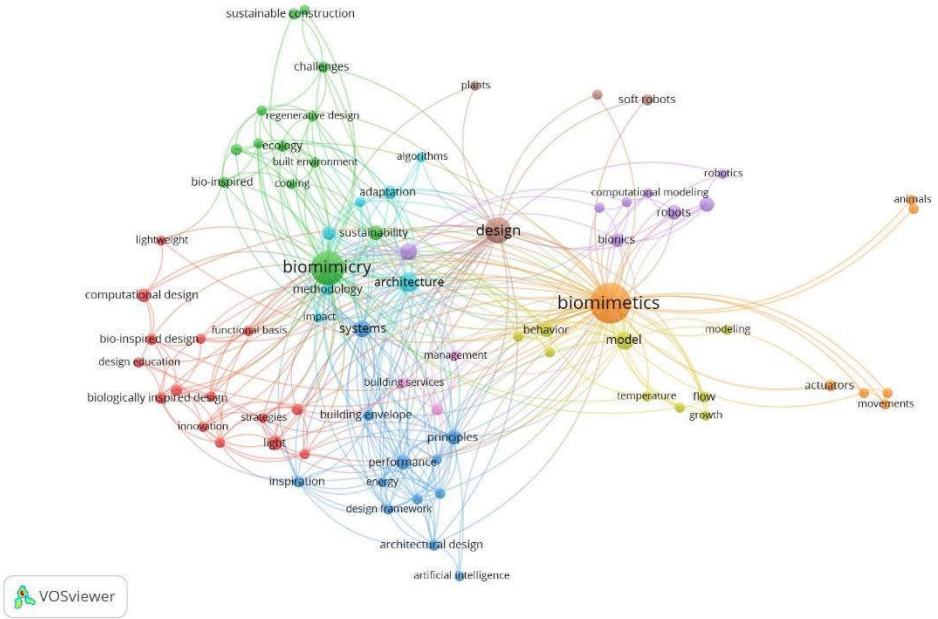

Figure 5. Network visualization of keywords co-occurrences of data included

3.5. Publicion source

Figure 6 shows the bibliographic analysis by document source and the relationship between publications and citations. The minimum number of documents is set at 1. The size of the node is proportional to the number of publications. The journals with the most documents are "Biomimetics" (5) and "Architectural design" (3). They are followed by "Bioinspiration and Biomimetics", "Sustainability" and Buildings.

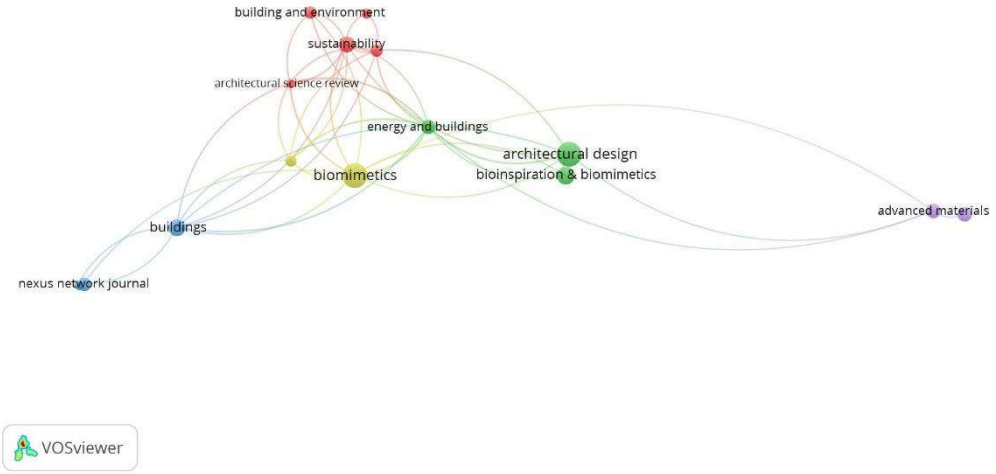

Figure 6. Visualization of publication sources' citations

Table 1 shows the distribution of documents and citations in the different journals (only sources with more than 1 document are considered in this table) and the total link strength, which is the total strength of links from one journal to other journals. The distribution of articles classified as biomimetic form and architectural design are mostly published in listed journals.

Table 1. List of journals with more than one publication about biomimetic architectural forms

Source	Documents	Citations	Total link strength
Biomimetics	5	138	16
Architectural design	3	152	12
Bioinspiration and Biomimetics	2	94	9
Sustainability	2	73	24
Buildings	2	68	18

3.6. Autorship analysis

In this chapter, the most cited authors whose articles are related to the topic of this paper are analyzed. Figure 7 shows the 6 authors with the most citations of their articles related to biomimetic form and architectural design. The highest number of citations (267), with a total link strength of 26, belongs to Achim Menges, based on the results from the cluster network. The other 6 authors with the most citations and their link strength are also shown in Table 2.

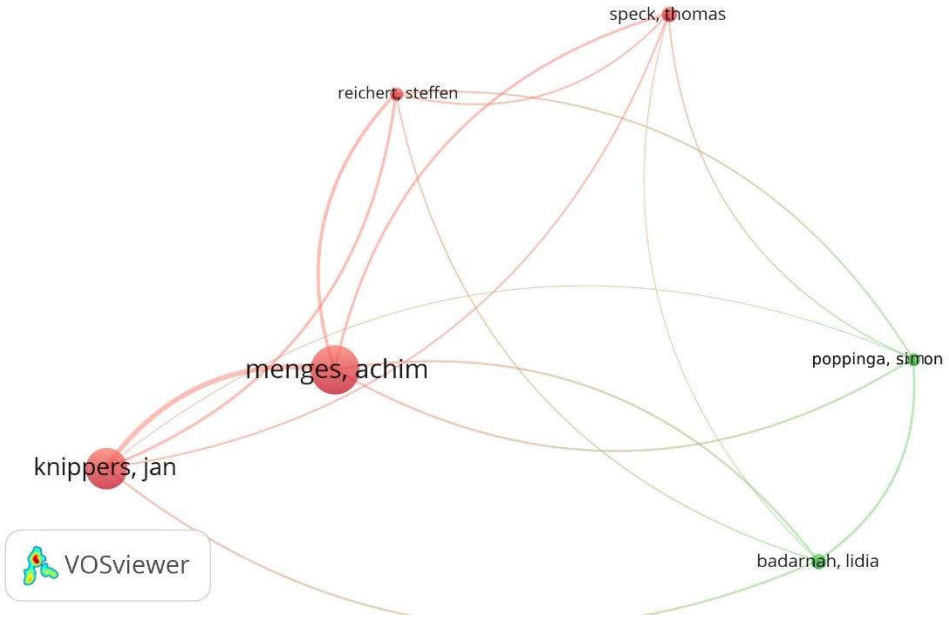

Figure 7. Visualization of the most cited authors

Table 2. List of authors with more than one publication about biomimetic architectural forms

Rank	Author	Document	Citation	Total link strength
1	Menges, Achim	7	267	26
2	Knippers, Jan	5	196	21
3	Speck, Thomas	4	165	13
4	Badarnah, Lidia	3	202	9
5	Poppinga, Simon	3	165	9
6	Reichert, Steffen	2	267	19

4. APPLICATIONS AND CHALLENGES

Based on the analyzed studies, it is evident that the largest number of studies represent the exploration of biomimetic architectural form through the design and fabrication of pavilions or building envelopes. A smaller number of studies deal with the methodology, review and challenges of biomimetic design [7-14].

4.1. Design strategies, tools and targeted performance in analyzed projects

Analyzed public building projects are generally characterized by scarce participation of biologists during the design process. The motive for applying the biomimetic approach was to provide a design with neutral to a positive impact on environmental issues, but almost none of them evaluated the final impact of the realized design. Kinetic building envelopes, ventilation or water regulation systems in buildings driven by technical equipment and operational energy have been recognized as bioinspiration. However, these cases lack an

interdisciplinary approach that involves the inclusion of biomimicry as a discipline and its methods in the initial design phase [15-23].

On the other side, academic projects present a strong correlation with biological contribution in their design process. These are mostly ephemeral structures - pavilions. Researchers from the Universities of Stuttgart and Freiburg are a perfect example of interdisciplinary collaboration [24-33].

It is important to identify common strategies and tools for successful transfer of biomimetic morphological principles to architectural design. What all academic projects have in common for a successful outcome is use of these transition tools and strategies:

1. Involving biologists and biomimetic tools in the initial design phase to understand principles from nature and their transfer into technology
2. Applying generative-performative design and parametric tools, where the building envelope is viewed as an intelligent adaptive system that reacts to the environment [34, 35]
3. Expertise in the field of building materials (bio-based materials) and their behavior, applying augmented reality, additive manufacturing, robotic manufacturing with a high degree of precision [36, 37].

Targeted performance achieved and applications:

1. Thermal comfort
2. Structural performance (less material), lightweight design
3. Indoor climate regulation (ecologically sensitive architectural surface)
4. Co2 reduction, less material waste

4.2. Challenges in implementation of biomimetic design approach

When it comes to such complex and developing approaches, one must talk about the challenges in its implementation. Based on the literature reviewed, this research defines the following groups of challenges:

1. Methodological challenges
2. Social challenges
3. Technological challenges

Some of the reasons explaining the low number of biomimetic products in architecture are the lack of a clear methodology, the difficulties of interdisciplinary work, and the complexity of biology as a model. In order for appropriate biomimetic design concepts to be generated with potential for commercialization, the systematic transfer of biological knowledge into technology needs to be facilitated and methods presented.

Similar to any new concept, people may show high level of resistance to change. Low level of technology acceptance, fear of working with unfamiliar practices, and heavy reliance on traditional practices are some of the main reasons for this resistance.

For the successful adoption of biomimetic buildings, stakeholders should focus on clearly demonstrating their sustainability credentials, rather than relying on their biomimetic nature as a stand-alone means of persuasion. Educational campaigns and public communication strategies should prioritize factual evidence of benefits, explicitly addressing environmental, economic, and social dimensions. There is no “biomimetic design language” that allows laypeople to judge biomimetic buildings or other products as inspired by living nature based on the characteristics of those buildings/products. The results highlight the importance of evidence-based communication of specific benefits and suggest that successful promotion

of biomimetic or bioinspired technologies requires a more nuanced understanding of public conceptualizations of sustainability [7].

Biomimetic strategies that integrate the structure, form and material of complex adaptive systems into a single heuristic process are one of the models in the research of digital morphogenesis in architecture. Digital tools expand the boundaries from the representation of space to the representation of systems. The main challenges in terms of technology and digital tools for biomimetic forms relate to bringing the language and symbols of new techniques of space representation closer to the user - the architect. A generative approach to modeling requires cognitive predispositions, and architects need an affinity for programming for such an approach to form generation [38].

5. CONCLUSION

Biomimicry is one of the most innovative approaches to energy-efficient design, and little research has been conducted in this area when it comes to architectural form. With the aim of better understanding this approach, presented review attempted to analyze the potential applications of biomimicry from the aspect of architectural form and identify the challenges that may be faced in adopting and implementing this approach.

The significant growth in the number of publications on this topic in recent years is shown by the Web of Science database, and the University of Stuttgart stands out in the number of publications and citations. Their example shows that cooperation between experts in biology and architecture is necessary to promote interdisciplinarity and achieve better results. According to this findings, architecture, biology and technology are deeply intertwined and multidisciplinary studies are inevitable.

The results of this study are relative given the rapid development of technologies and the possibility of introducing AI into the entire design process. Future studies could also address the evaluation of the most serious challenges in implementing a biomimetic approach in the design of architectural forms.

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REFERENCES

[1] Varshabi Niloufar, Selçuk Arslan Semra, Avinç Mutlu Günes: **Biomimicry for Energy-Efficient Building Design**: **A Bibliometric Analysis**. *Biomimetics,* Vol. 7, No. 21, 2022.
[2] Pawlyn, M: **Biomimicry in Architecture**. *RIBA Publishing*, London, UK, 2016.
[3] Benyus J.M: **Biomimicry Innovation Inspired by Nature.** *Morrow*: New York, NY, USA, 1997.
[4] Chayaamor-Heil Natasha: **From Bioinspiration to Biomimicry in Architecture: Opportunities and Challenges.** *Encyclopedia*, Vol. 3, No.1, 2023.

[5] Grant J. Maria, Booth, Andrew: **A typology of reviews: an analysis of 14 review types and associated methodologies.** *Health Information & Libraries Journal*, Vol. 26, No.2, 2009.
[6] Jan van Eck Nees, Waltman Ludo: **Visualizing bibliometric networks, in: D.W.Y. Ding, R. Rousseau (Eds.), Measuring Scholarly Impact: Methods and Practice.** *Springer*, Cham, Switzerland, 2014.
[7] Gorki Michael, Speck Olga et all.: **Challenging the Biomimetic Promise—Do Laypersons Perceive Biomimetic Buildings as More Sustainable and More Acceptable?.** *Biomimetics*, Vol.10, 2025.
[8] Badarnah Lidia, Kadri Usama: **A methodology for the generation of biomimetic design concepts**. *Archit. Sci. Rev*. Vol. 58, 2015.
[9] Vitalis Louis, Chayaamor-Heil: **Forcing biological sciences into architectural design: On conceptual confusions in the field of biomimetic architecture.** *Frontiers of Architectural Research*, Vol. 11, 2022.
[10] Bijari Maryam, Aflaki Ardalan, Esfandiari Masoud: **Plants inspired biomimetics architecture in modern buildings: A review of form, function and energy**. *Biomimetics*, Vol. 10, 2025.
[11] Ayres Phil: **From mimicry to Cuupling: Some diferences, Challenges and Opportunities of Bio-Hybrid Architectures**. *Architectural design*, Vol. 91, 2021.
[12] Nadeem Butt Anosh, Dimitrijevic Branka: **Multidisciplinary and Transdisciplinary Collaboration in Nature-Based Design of Sustainable Architecture and Urbanism**. *Sustainability*, Vol.14, 2022.
[13] Ortega Del Rosario Maria, Beerman Kimberly, Chen Austin Miguel: **Environmentaly responsive materials for building envelopes: a review on manufacturing and biomimicry-based approaches**. *Biomimetics*, Vol.8, 2023.
[14] Al-Masrani Salwa, Al-Obaidi Karam, Zalin Nor, Isma Aida: **Design optimisation of solar shading systems for tropical office buildings: challeneges and future trends.** Solar energy, Vol. 170, 2018.
[15] Badarnah Lidia: **Form follows environment: Biomimetic approaches to building envelope design for environmental adaptation**. *Buildings*, Vol.7, 2017.
[16] Peeks Megan, Badarnah Lidia: **Textured building facades: Utilizing morphological adaptations found in nature for evaporative cooling**. *Biomimetics*, Vol. 6, 2021.
[17] Rupp Ariana, Gruber Petra: **Bio-inspired evaporation from shaped interfaces: an experimental study**. *Bionspiration&Biomimetics*, Vol 4. 2021.
[18] Yoon Jungwon, Bae Sanghyun: **Performance evaluation and design of thermo-responsive SMP shading prototypes**. *Sustainability*, Vol. 12, 2020.
[19] Lopez Marlen, Rubio Ramon, Martin Santiago, Croxford Ben: **From plants to architecture: Biomimetic principles for development of adaptive architectural envelopes.** *Ren. and sust. energy reviews*, Vol 67, 2017.
[20] Bai Hao, Wang Lin, Ju Jie, Sun Ruize et all: **Efficient water collection on integrative surfaces with star-shaped wettability patterns**. *Advanced materials*, Vol.26, 2014.
[21] Cruz Estelle, Hubert Tessa, Chanoco Ginaud, Naim Omar et al.: **Design processes and multi-regulation of biomimetic building skins: A comparative analysis**. *Energy and buildings*, Vol. 246, 2021.
[22] Jalali Sara, Alibadi Morteza, Mahdavinejad Mohammadjavad: **Learning from plants: a new framework to approach water-harvesting design concepts.** *Int*. *Journal of building Pathology and adaptation*, Vol 40, 2021.
[23] Kuru Aysy, Oldifield Philip, Bonser Stephen, Fiorito Francesco: **A Framework to achieve multifunctionality in biomimetic adaptive building skins**. *Buildings*, Vol. 10, 2020.

[24] Poppinga Simon, Zollfrank Cordt, Prucker Oswald, Ruhe Jurgen, Menges Achim, Cheng Tiffany, Speck Thomas: **Toward a New Generation of Smart Biomimetic Actuators for Architecture**. *Adv. Mater*, Vol.30, No.19, 2018.

[25] Schleicher Simon, Lienhard Julian, Poppinga Simon, Speck Thomas, Knippers Jan: **A methodology for transfering principles of plant movements to elastic systems in architecture**. *Computer-aided design*, Vol.60, pp. 105-117, 2015.

[26] Reichert Steffen, Menges Achim, Correa David: **Meteorosensitive architecture: Biomimetic building skins based on materially embedded and hidroscopically enabled responsivness**. *Computer-aided design*, Vol. 60, 2015.

[27] Garufi Dominga, Knippers Jan et all.: **Fibrous Joints for Lightweight segmented timber shells**. *Research Culture in Architecture*, pp.53-64, 2019.

[28] Körner Axel, Born Larissa, Bucklin Oliver, Menges Achim, Knippers Jan: **Integrative design and fabrication methodology for bio-inspired folding mechanisms for architectural applications**. *Computer-Aided Design*, Vol.133, 2021.

[29] Poppinga Simon, Correa David, Bruchmann Bernd, Menges Achim, Speck Thomas: **Plant movements as concept generators for the development of biomimetic compliant mechanisms**. *Integrative and comparative biology*, Vol.60, 2020.

[30] Dierichs Karola, Menges Achim: **Designing architectural materials: from granular form to functional granular material**. *Bioinspiration&Biomimetics*, Vol. 16, 2021.

[31] Knippers Jan: **The use of biological models for building engineering design**. *Physical models*, pp.1005-1016, 2020.

[32] Doerstelmann Moritz, Knippers Jan, Koslowski Valentin et all.: **ICD/ITKE Research Pavilion 2014-15: Fibre Placement on a Pneumatic Body based on a Water Spider Web**. *Architectural design*, Vol. 85, 2015

[33] Takahashi Kenryo, Kiesewetter Laura, Koerner Axel, Wood Dylan: **Structural design and construction of a self-shaping single curved timber structure HygroShell**. *IASS 2024 Symposium*, Zurich, 2024.

[34] Maslov Dmytro, Cruz Fabio et all. : **Functional conception of biomimetic artificial reefs using parametric design and modular construction**. *Marine science and engineering,* Vol. 12, 2024.

[35] Yi Hwang, Kim Yuri: **Prototyping of 4D-printed self-shaping building skin in architecture: Design, fabrication, and investigation of a two-way shape memory composite (TWSMC) facade panel**. *Journal of building engineering*, Vol. 43, 2021.

[36] Cheng Tiffany, Menges Achim et all.: **Weather-responsive adaptive shading through biobased and bioinspired hygromorphic 4D-printing**. *Nature communications*, Vol.15, 2024.

[37] Pasquero Claudia, Poletto Marco: **Beauty as Ecological Inteligence: Bio-digital Aestethics as a Value System of Post-Antropocene Architecture**. *Architectural design*, Vol. 89, 2019.

[38] Tepavcevic Bojan: **Influence of geometric representation of space on contemporary architecture**. PhD Thesis. *Faculty of Technical Science*, Novi Sad. pp.216-224, 2010.