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BIOMIMETIC APPROACH FOR ADAPTIVE, RESPONSIVE AND KINETIC BUILDING FACADES: A BIBLIOMETRIC REVIEW OF EMERGING TRENDS

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Abstract. Nature serves as a data source for many disciplines, offering strategies such as sensitivity, adaptability, robustness, high resilience, lightness, energy efficiency, self-healing and self-improvement. The characteristics within this data pool provide alternatives for solving similar problems in different disciplines. Terms such as biomimicry, bio-informed, bio-inspired, nature-inspired, used to denote the process of deriving solutions from natural strategies, involve learning and adapting from nature. It is recognized as a significant tool not only in fields such as engineering, materials and robotics but also in the advancement of architectural knowledge. In recent years, research has prominently focused on adaptive, adaptive and kinetic biomimetic facade designs for energy efficiency. Within the scope of this study, publications on adaptive, adaptive and kinetic biomimetic facades were systematically reviewed and the state of the literature and contributions to the field were highlighted using bibliometric methods. In this context, a search was conducted in the Scopus database using predefined keywords to access relevant studies, evaluating aspects such as publication years, types of publications, countries of publication, Scopus category of the article, journal names and frequently used keywords. Subsequently, a content analysis was conducted for the most cited studies. As a result, it was observed that biomimetic adaptive/sensitive/kinetic facade designs in architecture, particularly in the context of energy efficiency, contribute to innovative studies, addressing aspects such as thermoregulation, natural ventilation and the use of renewable materials.

Keywords: *Biomimetics, adaptive, responsive, kinetic, building facade, bibliometric analysis.*

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1. Introduction

"Contemporary architecture and the culture it reflects dependent as it is on fossil fuels, has contributed to the cause and necessity of a burgeoning green process that emerged over the past half century" (Tabb & Deviren, 2017). For this reason, in recent years, research on adaptive, responsive and intelligent building facades has garnered significant attention (Körner *et al*., 2017). The building envelope is identified as a crucial design element due to its leadership in maintaining comfortable indoor temperatures (Fecheyr-Lippens & Bhiwapurkar, 2017; Badarnah, 2017; Sadineni *et al*., 2011). Additionally, the building envelope is described as the interface between external environmental factors and the internal demands of building occupants, without distinction between roofs and walls (Del Grosso & Basso, 2010). Therefore, 'building envelopes, architectural claddings or facades' serve as filters between external

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environmental conditions and the expected requirements of the interior space, playing a significant role in the regulation and control of energy consumption (Lopez *et al*., 2017).

Based on this, research is being conducted to enhance energy efficiency in building envelopes, architectural claddings or facades, focusing on aspects such as lighting, heating, water management, ventilation, cooling and the utilization-management of solar energy. Generally, static design solutions for facades, which play a crucial role in controlling energy consumption in buildings, have been emphasized. However, the energy efficiency provided by these designs often requires a substantial amount of energy consumption to sustain indoor comfort (Lopez *et al*., 2017). As known, buildings are held responsible for 36% of CO_2 emissions and 40% of energy consumption. In this context, the European Council aims to reduce greenhouse gas emissions to 80-95% below 1990 levels by the year 2050 (European Commission, 2011).

In this context, some of the research aimed at this goal involves the implementation of adaptive/sensitive/kinetic facade designs using a biomimetic approach. The biomimetic approach, which entails the transfer of processes, systems and strategies existing in nature, is a continually evolving discipline in various fields such as engineering, robotics, medicine, art and architecture. This approach involves investigating solutions in nature for identified problems. To achieve this, researchers explore how organisms in nature capture, convert, store and process energy, water and sunlight. Additionally, the research focuses on understanding how nature cools, heats, provides shade and controls light.

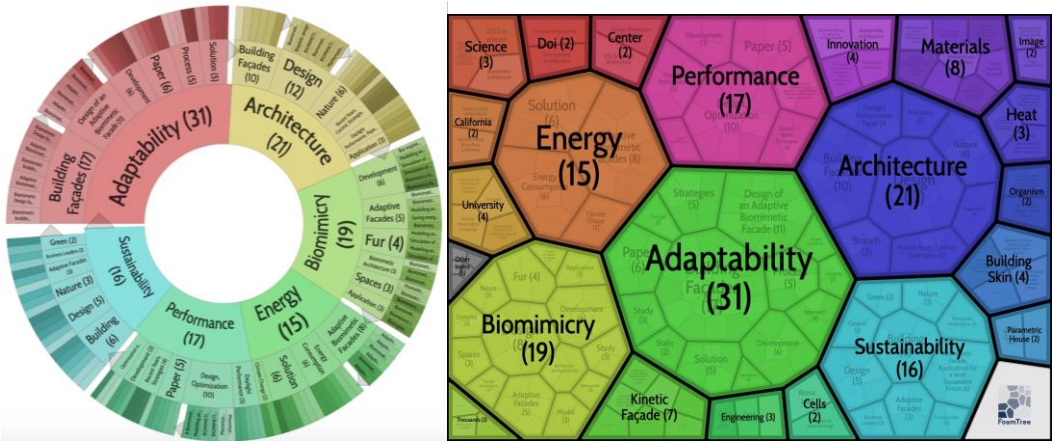

Figure 1. Concepts discussed together with "biomimetic façade solutions" in Carrot Search (URL-1)

To identify the concepts underpinning biomimetic facade solutions and the strategies derived from nature, clustering analysis was conducted on the Carrot Search (URL-1) database using the term 'biomimetic façade solutions'. The results are depicted in the 'visual information map' (Figure 1). The sizes and angles of the bubbles in Figure 1 represent the relationship between the subject and the number of documents. Within the visual on the right side of Figure 1, a total of 27 clusters are identified, demonstrating varying subject sizes and distributions. In the same visual, it is observed that terms such as 'energy efficiency', 'façade systems', 'biomimicry', 'climate' are frequently used in conjunction with terms like 'adaptive', 'kinetic' and 'responsive.

As identified frequently in this research, the concept of 'Adaptability' is defined as the ability of a system/organism to respond to changing internal and external environmental conditions. Additionally, the adaptive approach has a broader perspective than the responsive concept, as it aims to enhance functionality and optimize waste reduction, addressing issues such as energy consumption and the availability of material resources (Al-Obaidi *et al*., 2017). One of the fundamental motivations in examining these issues is to achieve improved performance in areas such as thermoregulation and energy efficiency by enabling buildings to adapt to both internal and external environmental conditions.

In the literature, "adaptive, responsive and kinetic building facades" are frequently studied by different researchers. For example, in the study by Alani and Kahera (2023), a shading element was placed on the facade to prevent direct sunlight from entering the room and maximize the view and simulation studies were conducted to test its effect. The study conducted by Hays, Badarnah and Jain (2024) investigates "transferring the morphological characteristics of elephant skin to building facades and optimizing their natural cooling capabilities through computational design using evolutionary algorithms". On the other hand, Bagheri-Moghaddam et al. (2023) "aims to present a generative design-based prototype of a biomimicry green façade substrate with photosynthetic microorganisms to enhance building façade efficiency". Similarly, López et al. (2017) develops a design map for transferring knowledge from plant adaptations to architecture and two design concepts that show the potential of the plant. Varshabi et al. (2022) analyzed articles published in the Web of Science database (2010-2021) using VOSviewer and SankeyMATIC software for bibliometric analysis of research on biomimicry and energy efficiency. Faragalla and Asadi (2022) conducted a comprehensive literature review to review biomimetic methodologies developed to design adaptive facades. Shashwat et al. (2023) "a detailed analysis is presented in this study to understand the current trends and research gaps in achieving an energy-efficient built environment". As a result, as it is understood from these reviews, there is no bibliometric study on "adaptive, responsive and kinetic biomimetic façade research".

From this point of view the aim of this study is to perform a bibliometric data and content analysis on biomimetic facade research focusing on adaptability, responsiveness and kinetics, designed with strategies derived from nature. For this purpose, data obtained from a search conducted in the Scopus database was analyzed using the Bibliometrix program.

2. Methodology

2.1. Research Design

The exploration of scientific literature spans a long history, covering a continuity that extends up to the first decade of the last century. However, despite the density of research in this field, the term 'bibliometrics' first emerged in print in 1969 (Andres, 2009). Bibliometrics is a field that examines bibliographic data, such as scientific publications and citations and is utilized to comprehend trends, interactions and knowledge production in the scientific community. In light of this, bibliometric mapping is employed in this study to analyze articles on adaptive, responsive and kinetic biomimetic facades from various parameters. These mapping types typically depict relationships among entities like authors, documents, journals or keywords, often based on citation, co-citation, bibliographic coupling data or the co-occurrence of

keywords in documents (Van Eck *et al*., 2010). The bibliometric approach, defined as 'a set of quantitative methods used to measure, track and analyze printed scientific literature', maps the landscape of a research field (Roemer & Borchardt, 2015). Utilizing coded bibliographic information from scientific databases (such as Web of Science, Scopus, PsycINFO, ERIC), bibliometric analysis examines trends in publication and citation data, contributions of authors, institutions and countries to the development of the field, scientific collaboration networks and the distribution of publications among journals and disciplines (Andres, 2009). Bibliometric reviews of the literature provide a comprehensive picture of the development and current state of a field, allowing for the processing of much higher-volume studies published over a longer period with less time and resource investment (Hernández-Torrano & Ibrayeva, 2020).

One of the objectives of the study is to determine the scientific literature structure in adaptive/responsive/kinetic biomimetic facade research, including institutions, universities, authors, most-cited articles and keywords. Additionally, the identification of potential future research areas and research gaps is aimed at. Thus, the results of this research can be utilized to comprehend developments in this field, identify trends and provide guidance for future research. In this context, the research questions guiding this study are as follows:

- What is the numerical distribution of academic publications on adaptive/ responsive/kinetic biomimetic facades over the years?
- Which journals are actively involved in academic research on adaptive/ responsive/kinetic biomimetic facades?
- What is the citation count of academic publications on adaptive/ responsive/kinetic biomimetic facades?
- Which countries are actively involved in academic research on adaptive/ responsive/kinetic biomimetic facades?
- What is the keyword network status of academic publications on adaptive/ responsive/kinetic biomimetic facades?
- Who are the authors of academic publications on adaptive/responsive/kinetic biomimetic facades?

2.2. Obtaining the Data Set

This study was carried out using the Scopus database. Developed in 2004 by Elsevier, the Scopus database is described as a high-quality bibliometric data source for academic research (Baas *et al*., 2020). In this context, 111 publications were obtained as a result of the search in the “Scopus” database on 20 October 2022 using the query term presented in Figure 2. The research was conducted with the keywords biomimetic, biomimicry, bioinspired, bio-inspired nature inspired, adaptive, responsive, kinetic, deployable, facade, envelope. All studies reached within the scope of the study were evaluated by bibliometric analysis.

In the study, the studies searched for “Article title, Abstract, Keywords” in English from Scopus (URL-2) database were used. (TITLE-ABS-KEY (“biomimetic” OR “biomimicry” OR “bioinspired” OR “bio-inspired” OR “nature inspire”) AND TITLE-ABS-KEY (“facade” OR “envelope”) AND TITLE-ABS-KEY (“adaptive” OR “responsive” OR “kinetic” OR “deployable”))), a total of 111 studies were found (Figure 2).

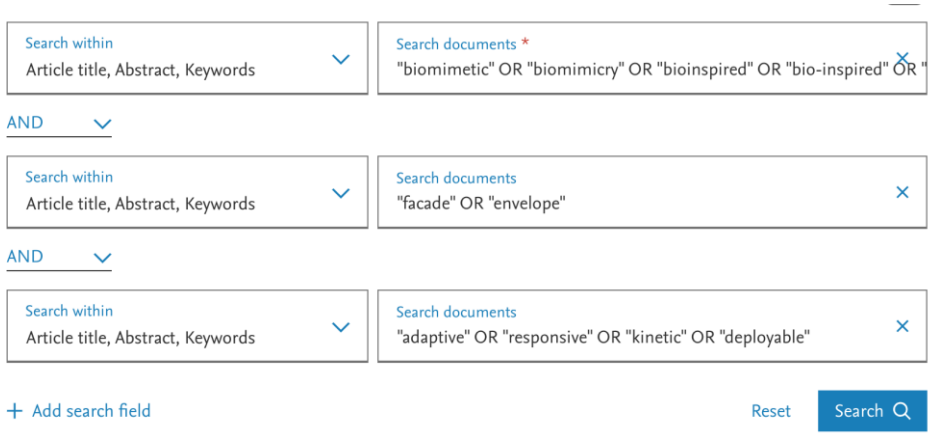

Figure 2. Search in the Scopus database

2.3. Data Analysis

The metadata of relevant articles published in SCOPUS were downloaded in BibTeX (.bib) file format and subsequently, an R program tool called 'biblioshiny for bibliometrix', operating in RStudio Version (4.3.1.), was utilized for analysis. The Bibliometrix software, developed by Massimo Aria and Corrado Cuccurullo, is a reliable, open-source tool for conducting science mapping analyses of the scientific literature (Aria & Cuccurullo, 2017). Biblioshiny is defined as an application that provides a web interface for bibliometrix (URL-3).

3. Results and Discussion

3.1. General trends

Figure 3 shows the distribution of the number of studies by years. When this graph is analysed, it is seen that the first publication started in 1997, no publications were produced between 1998-2005 and a significant increase was observed in 2022.

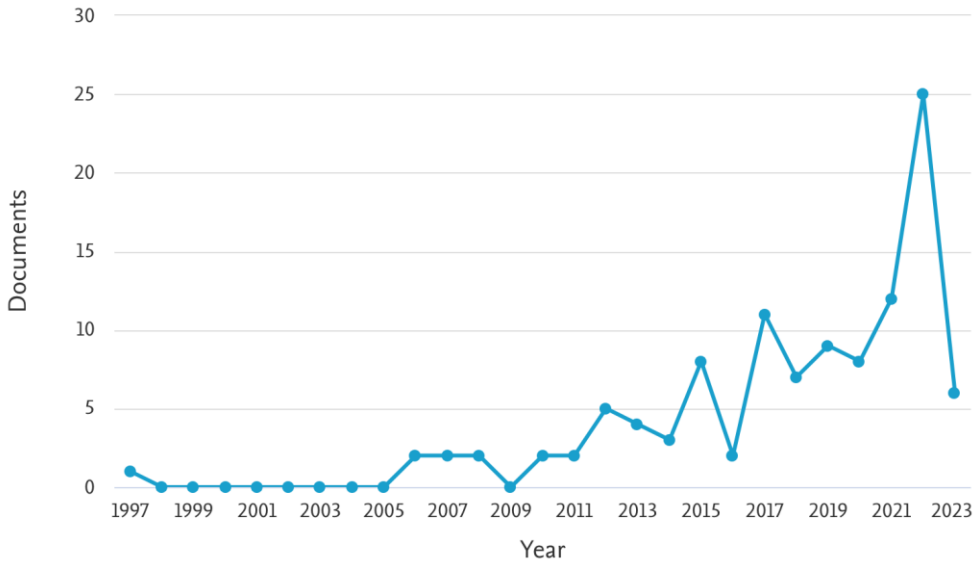

Figure 3. Distribution of the number of studies reached by years (1997-2023)

Among the studies accessed, article (48; 43.2%), conference paper (31; 27.9%), book chapter (12; 10.8%), review (10; 9%), conference review (9, 8.1%) and book (1, 0.9%) were determined (Figure 4).

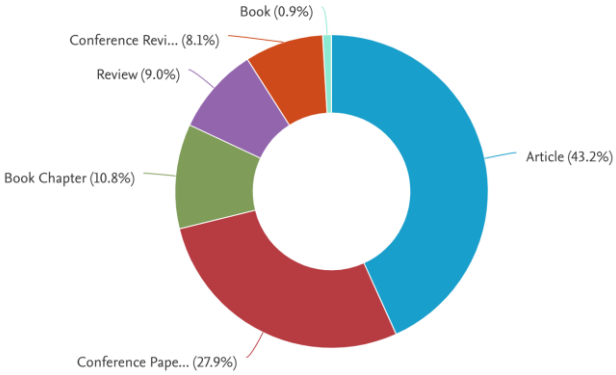

Figure 4. Classification of accessed documents according to type

The descriptive data of the obtained studies are presented in Table 1. Table 1 indicates that the research based on keywords resulting from the search in Scopus started with the first publication in 1997 and has continued to increase until the present. The analysis conducted with the Bibliometrix R package reveals that studies on biomimetic design for adaptive, responsive and kinetic building facades have shown an annual growth rate of 7.13% in scientific production from 1997 to 2023. However, the average citation rate per document is 14.82. In this research, which involves a total of 290 authors, the number of single-authored documents is 9. There is an average of 3.47 co-authors per document (Table 1).

Table 1. Descriptive data of the studies obtained

Description	Results
Timespan	1997:2023
Sources (Journals)	89
Documents	110
Annual Growth Rate	%7,13
Average citations per doc	14,82
Authors	290
Single-authored docs	9
Co-Authors per Doc	3,47

3.2. Documents by country or territory

The search results obtained from the Scopus database were analysed according to the countries where the studies were produced. The findings related to the first ten countries are presented in Figure 5. Accordingly, it is seen that the countries producing the highest number of publications are Italy, United States and Australia, respectively.

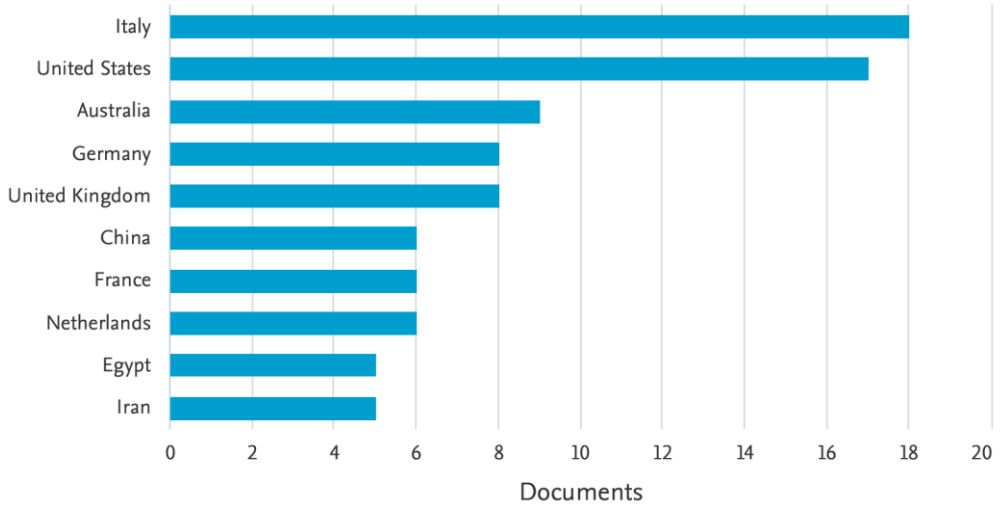

Figure 5. Comparing document numbers for up to 10 countries/regions

3.3. Most Relevant Journals

According to the search and filtering in the Scopus database, 110 articles on biomimetic design for adaptive, responsive and kinetic building facades have been published in 89 journals (Table 1). Figure 4 presents the 'Bradford Law' graph, which depicts the order and numbers of articles in the journals where these articles were published. Bradford's Law of Scattering defines the 'dispersion or distribution of literature in journals on a specific subject' (Garfield, 1980). The graph ranks journals based on the number of publications and visually represents the titles of journals in the first group (Figure 6).

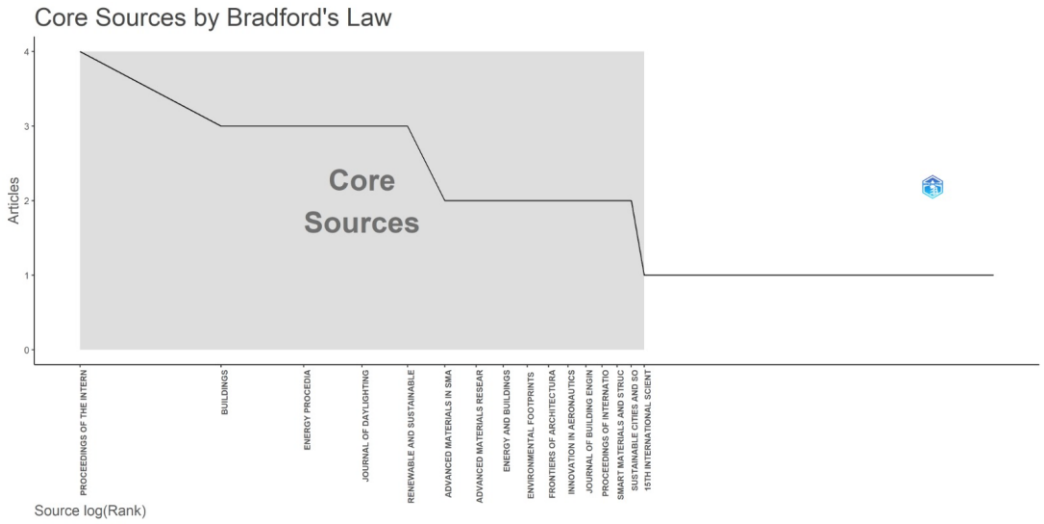

Figure 6. Bradford's Law Analysis Journal Ranking

3.4. Most Relevant Universities and Countries

In the search conducted on the Scopus database, the University of Stuttgart has been the most prolific institution with 11 research articles among the 110 studies retrieved. Figure 7 provides numerical information about the top 20 institutions related

to the topic. The performance of organizations with two or more publications on biomimetic design for adaptive, responsive and kinetic building facades can be seen in Figure 6. Thus, the University of Stuttgart has been identified as the most productive research center with the highest number of publications (11) in the context of the research topic. Following this university, the University of New South Wales in Sydney, Australia (8) and the University of Freiburg in Germany (6) are ranked as the second and third universities with the most publications, respectively.

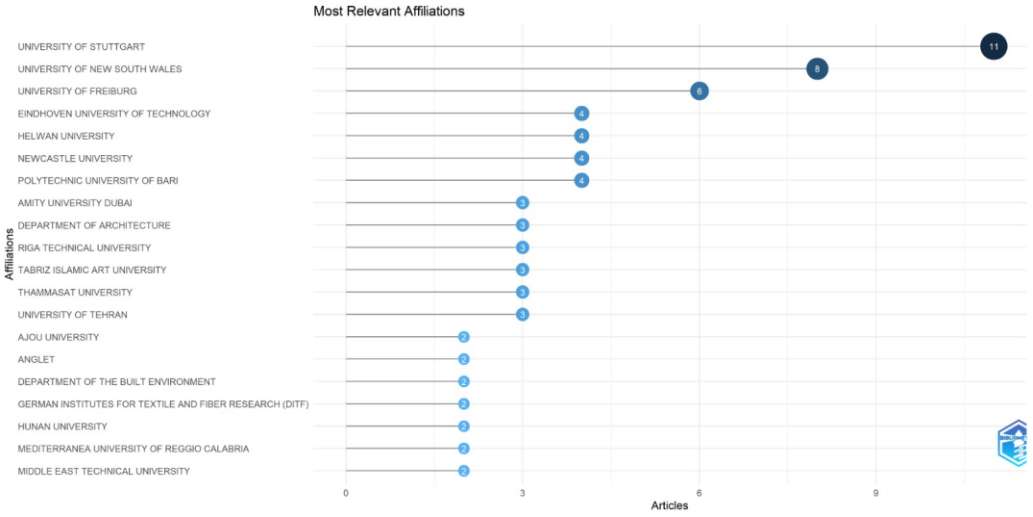

Figure 7. The Most Relevant Affiliations according to the Number of Articles

3.5. Most Relevant Authors

In the search conducted on the Scopus database, it was observed that 290 different authors have published on the topic of biomimetic design for adaptive, responsive and kinetic building facades. Among these authors, 9 have produced articles individually, while 290 have collaborated (Figure 8). Figure 8 provides numerical information about the top 20 authors relevant to the topic.

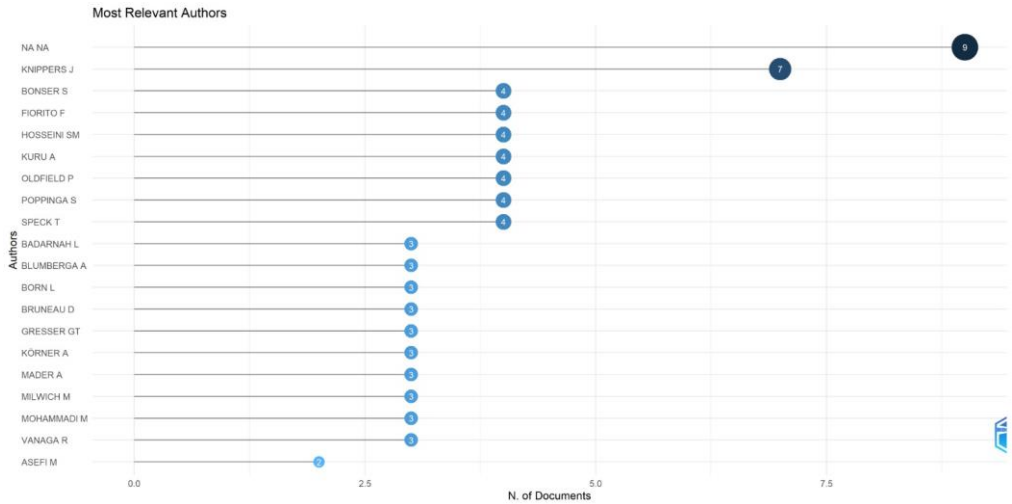

Figure 8. The Most Relevant Authors according to the Number of Articles

In bibliometric analyses, the number of publications per year is tracked to observe how authors' productivity changes over time. Thus, trends in the increase or decrease in authors' productivity and information on how active they are in a particular topic or field are revealed. In this context, Figure 9 illustrates the productions over time of researchers who have the most publications in this field.

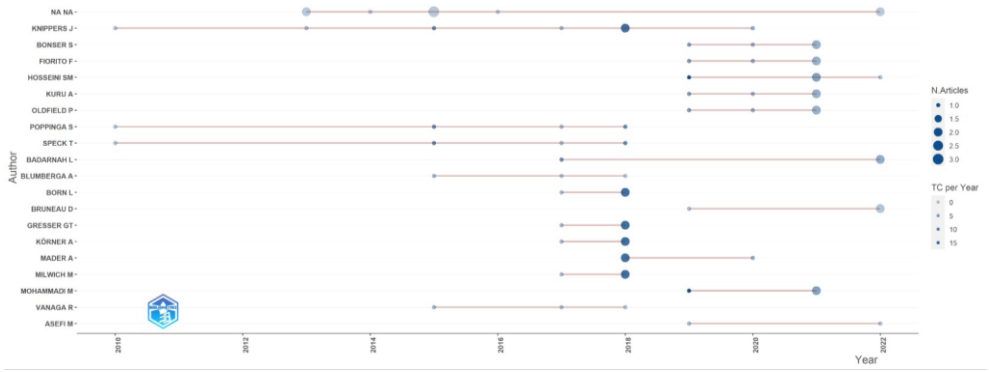

Figure 9. Author' production over time

3.6. Keywords and Trend Topics

Figure 10 presents the most frequently used keywords in the accessed studies. In this context, the most commonly used keywords are biomimetics (f:43), architectural design (f:21), energy efficiency (f:16), biomimicry (f:10), sustainable development (f:10), buildings envelopes (f:9), solar buildings (f:8) and energy utilization (f:7).

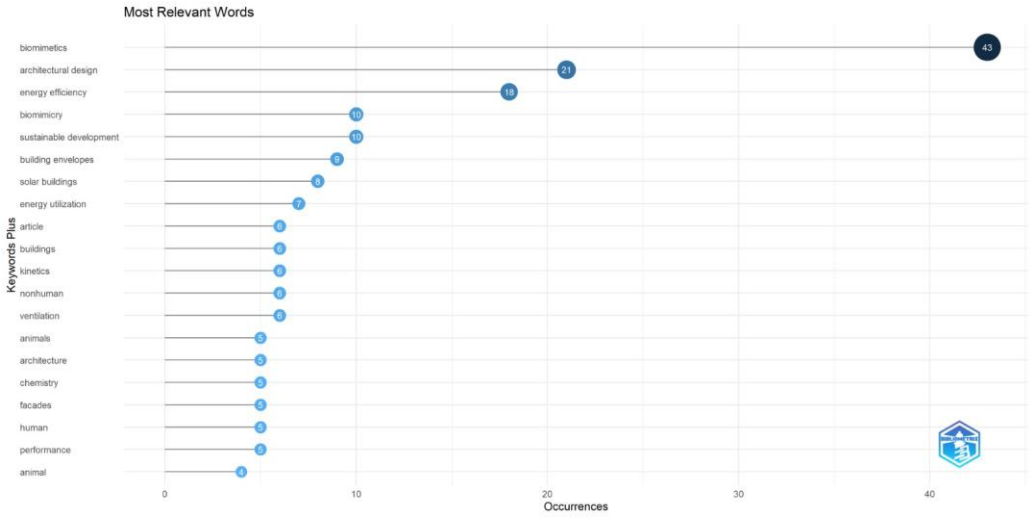

Figure 10. Most Relevant Words

The co-occurrence network is a method used to analyze the frequency of specific words appearing together in a text or document. This network is employed to visualize relationships and connections between words. Associating keywords with publication content serves as a guide to reveal trends in research topics. Through this analysis, it was determined that the keywords "Biomimetics", "architectural design", "energy

efficiency", "buildings envelope" and "solar buildings" are the most frequently connected keywords for authors (Figure 11).

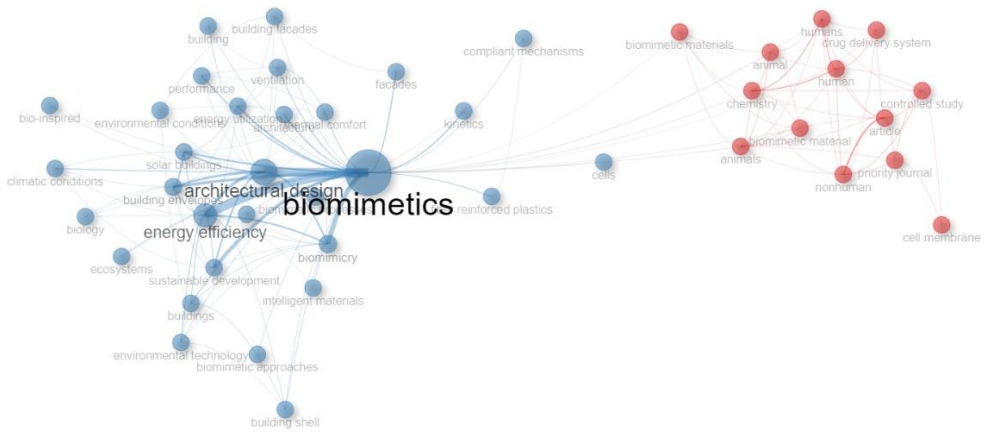

Figure 11. Co-Occurence of Keywords

In Figure 12, it is observed that in studies related to biomimetic design for adaptive, responsive and kinetic building facades, topics such as ventilation, performance, energy utilization, sustainable development, energy efficiency and solar buildings have gained significance.

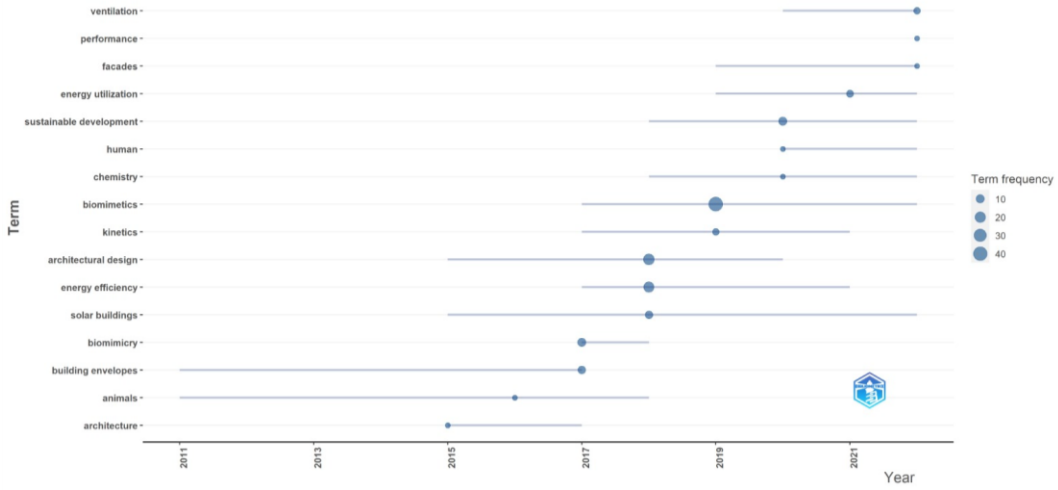

Figure 12. Trend Topics

3.7. Sunkey Diagram

The three-domain graph of author, keyword and themes is illustrated in Figure 10. In the Sankey diagram, the height of each box and the thickness of connecting lines indicate prominent headings. The longer the colored box is, the more significant it is considered. Additionally, the thickness of correlation lines representing connections signifies the productivity of information or workload (Figure 13). In this context, concepts such as biomimetics, biomimicry, biomimetic, kinetic façade, building envelope are observed to be the most frequently used keywords.

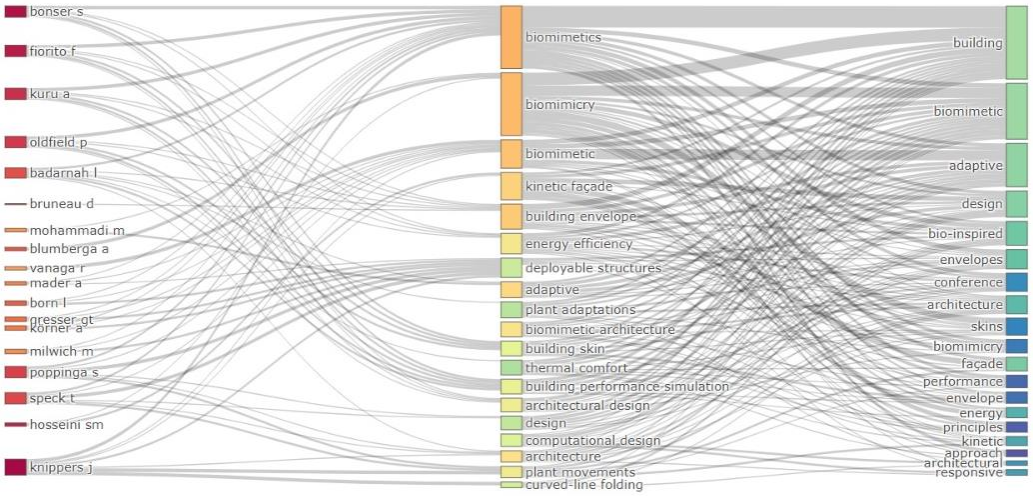

Figure 13. Three-Field Plot

3.8. Content Analysis of Selected Articles

Table 2. Content analysis of the most cited articles

No	Description	Reference
1	Investigating the possibility of adaptive building systems with the use of hygromorphic materials in architecture	Holstov et al. (2015)
2	To design adaptive architectural envelopes by learning from plant adaptations using biomimicry approach	Lopez et al. (2017)
3	A morphological investigation into the kinetic facade design process to improve visual and thermal comfort	Hosseini et al. (2019)
4	A methodology for transferring the principles of plant movement to elastic systems in architecture	Schleicher et al. (2015)
5	Investigating adaptive biomimetic building shell designs, mechanisms, functions and materials	Al-Obaidi (2017)
6	Development of biomimetic responsive material systems that do not require an external energy source and mechanical or electronic control	Menges and Reichert (2012)
7	Laboratory-scale material development to investigate the applicability of wood-based hygromorphic materials for large-scale structures	Holstov et al. (2017)
8	Study of natural morphologies in order to develop new technological solutions with reference to nature in order to improve the environmental adaptability of buildings	Badarnah (2017)
9	Production of an adaptable facade shading device that can move without hinges	Körner et al. (2017)
10	Adaptive biomimetic façade design research as a solution to improve the energy efficiency of highly glazed buildings in hot and humid regions	Sheikh and Asghar (2019)
11	Examination of examples within the scope of building physics and energy efficiency and review of adaptive design support methodologies	Loonen (2014)
12	Description, classification and comparative analysis of existing applications in the field of biomimetic adaptive building envelopes	Kuru et al. (2019)
13	Hingeless design inspired by the Flexagon pattern of insect hind wings and the hierarchical structure of the wing cuticle of the shield bug (Graphosoma lineatum)	Schieber et al. (2017)
14	Thermoregulation façade design inspired by the adaptive strategies of the African cane toad and the Hercules beetle	Fecheyr-Lippens and Bhiwapurkar (2017)

15	Biomimetic adaptive facade design with reference to chameleon skin	Bui et al. (2021)
16	Kinetic adaptive biomimetic facade and wall design solution	Vanaga and Blumberga (2015)
17	Active, dynamic and intelligent facade designs in high-rise building design	Jafari and Alipour (2021)
18	Biomimetic adaptive building facade design	Kuru et al. (2020)
19	Design of a hingeless and harmonious facade shading element inspired by plant movements	Mader et al. (2020)
20	Bio-inspired kinetic envelope system design	Wang and Li (2010)

In this section of the study, a content analysis has been conducted on the top 20 most cited articles to better understand, analyze and interpret the research conducted on biomimetic design for adaptive, responsive and kinetic building facades (Table 2).

Within the examined studies, it is observed that biomimetic facade research focusing on responsive, adaptive and kinetic designs provides solutions to issues such as energy efficiency and thermoregulation. Therefore, designs that operate without the need for an external energy source are produced to reduce energy consumption. Additionally, these designs often explore the use of hygromorphic materials in architecture. These studies generate solutions by learning from systems and strategies found in nature, such as cones, insects, frogs and chameleons.

4. Discussion and Conclusion

In this study, a bibliometric analysis of research on adaptive, responsive and kinetic biomimetic facades has been conducted. In order to present the current state of the literature, the years of publications, journals with the most publications, countries, universities, authors and keywords related to the subject have been identified. Cluster analysis has been performed using the keywords found in the obtained research. In this context, the bibliometric analysis study reveals that the increasing number of studies represents an active research area in the field of adaptive, responsive and kinetic biomimetic facades.

As a result of this research, it has been observed that trends in facade design are developed as dynamic and kinetic systems. These systems are identified as climate-sensitive, thermoregulation, adaptable and flexible designs that do not require external energy sources, mechanical or electronic control and can move without hinges, while also being operable with an external source. Therefore, it can be stated that the biomimetic approach provides significant solutions for building facade systems to provide thermal comfort in a responsive, adaptable and kinetic manner. In conclusion, this review presents a summary of the literature for researchers in the field using bibliometric data analysis, visualization and content analysis.

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