

THE USE OF BIOMIMICRY IN ARCHITECTURE FOR SUSTAINABLE BUILDING DESIGN: A SYSTEMATIC REVIEW

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ABSTRACT

The environmental problems getting more chronic every day direct academics to design buildings considering the influence of nature. One of the most important methods of sustainable building design is biomimicry. The aim of this article is to examine the studies on the use of biomimicry in architecture, to raise awareness about sustainable building design and to create a guide for future researchers. It has been determined that most of the studies examined are in search of solutions for sustainable building design by examining nature. Studies on biomimicry, especially in architectural education, try to raise awareness to understand its importance in terms of sustainability by including this subject in architectural education instead of examining nature. The combination of simulation technique and field research technique is the most preferred method for the use of biomimicry in sustainable building design. It is thought that this study will be a guide on how to reveal the mysteries of nature for sustainable building design and the criteria that should be emphasized in order to reveal these mysteries. In addition, it is thought that it will create awareness about the use of biomimicry in architecture in sustainable building design.

1. INTRODUCTION

Environmental problems such as depletion of natural resources, global warnings and increase in energy consumption have directed architects and designers to sustainable building. Reduced number of natural resources, environmental problems getting chronic and increased energy consumption direct architects and designers to eco-friendly and sustainable building. The main purpose of sustainable building is to reduce the negative impact of people on the natural environment. Buildings that are not designed according to the climate and topography criteria of their location consume high levels of energy to provide indoor comfort (Eray & Kutlu, 2021). Brownell and Swackhamer (2015) suggest that one of the most important design practices designers as well as architects and scientists who observe nature should prefer is biomimicry. The main purpose of the use of biomimicry in architecture is to design a building inspired by the adaptations of organisms or systems in nature to their environment (Ergün & Aykal, 2022; Sheikh & Asghar, 2019).

The concept of biomimicry was introduced by Otto Herbert Schmitt, a biophysicist and engineer, during 1950s but it was developed by Benyus (Vincent et al., 2006). Biomimicry consists of the Latin terms “bios” and “mimicos”. Biomimetic or biomimicry (the term “biomimicry” will be used in this study) observes the nature and gets influences by it to solve people’s problems. Tavsan, Tavsan, and Sonmez (2015) briefly defined biomimicry as the innovation influenced by nature, which suggests that biomimicry is an extensive reflection of nature.

Engin et al., (2020) stated that nature has taken on an inspiring role in design fields from the past to the present. Designing buildings inspired by nature has been going on since ancient times. However, the reflections of nature have been in different dimensions in the modern and ancient periods. It was limited with the dimensions or shape of a natural form in ancient buildings (Ramzy, 2015). Exploration of pillars resembling to palm tree or displaying lily pad motives in ancient Egypt proves the aforementioned result.

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One of the most important reasons for using biomimicry in contemporary architecture is to design sustainable buildings. Inspired by systems and processes based on biology in contemporary architecture and used in building designs (Benyus, 1997; Zari, 2007). Benyus (1997) evaluated the use of biomimicry in building design in three stages, from shallow (limited scope) to deep (extensive scope), according to the level of inspiration from nature (Figure 1).



Figure 1: Stages of using nature in architecture

Organism level is the use of the traits of any plant, animal or organism during the process of creating building form, being the basic stage of imitating nature. Behavioral level is the imitation of a creature's methods of adapting to the nature within the building design. Ecosystem level is the level of imitating more than one condition required for a creature for the ecosystem it is present in, and it is the most extensive level of imitating nature (Ahmar 2011). There are five potential dimensions for each level of natural influence. A sample was formed for the organism level in Table 1 about the form of determining these dimensions (Zari, 2007).

Table 1: Definition and samples of five potential dimensions regarding the imitation within the organism level

Dimensions of imitation within the building	Definition	Example
Form	What does it look like?	Building form appears like a turtle.
Material	Which material was used for the construction?	Construction of the building with a material imitating the skin of a termite
Structure-- facade	How was it constructed?	The building skeleton was formed in the same manner of human skeleton.
Process	How does it work?	The building generates O2 using the methods a plant performs to generate the same.
Function	What can it do?	The building acts like a termite, generating soil by recycling cellulose waste.

The basis of biomimicry is to be inspired by organisms or processes in nature. However, the features to be inspired are sometimes hidden. The way in which these mysteries are uncovered and used for sustainable building design differs among researchers (Benyus, 1997; Chayaamor-Heil & Hannachi-Belkadi, 2017).

Hershcovich et al., (2021) analyzed the tissues of organisms such as sponge and cacti in a computer environment. Later, inspired by these textures, he proposed a building envelope that would reduce building energy consumption. Xing et al., (2018) analyzed plant cell walls and building envelope comparatively in their study. Revealing the mystery in the design principles of plant cell walls, he made a suggestion for the application of the building envelope. Mandeel et al., (2021) made a building design proposal for a hot and dry climate by analyzing the external form and working mechanism of the Bottlebrush plant. These example can be increased (Table 4).

The aim of this paper is to systematically review the use of biomimicry in academia, to draw conclusions from them, to make suggestions in this context and to raise awareness about the sustainable building

design of biomimicry in architecture. Accordingly, two significant outputs were aimed:

- to perform assessment and collection by facilitating the access to the data such as purpose, methods and biomimicry dimension within the academic studies on biomimicry;
- to form a guide about the researchers working in this field.

Uchiyama, Blanco, and Kohsaka (2020) aimed in their study to compare biomimicry models in urban and architectural design even if they reviewed the literature on biomimicry in a systematic manner. Therefore, they conducted a basic process of grouping without detailing architectural studies (Table 4).

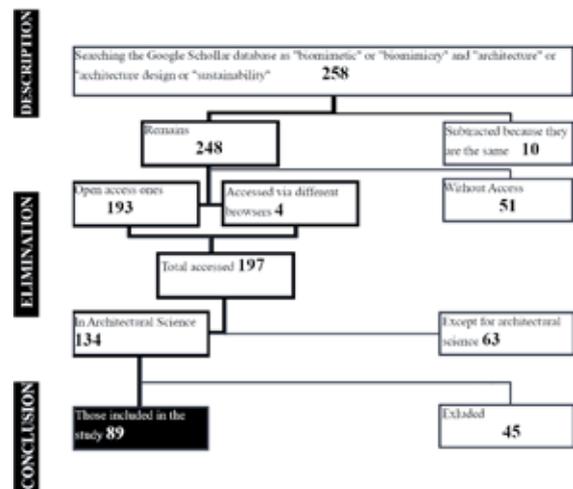
2. METHOD

To provide an overview of the current research, a systematic literature search was first conducted using the following research terms and combining them with Boolean operators (AND and OR): biomimetic*, biomimicry*, architecture*, architecture design*, and sustainability*. The method of using available information was used as an archive research method. During the data collection phase, "Google Scholar" was utilized as the main database, and "ResearchGate", "Academia" and "Mendeley" were also utilized. Although it was not possible to determine all current and newly published data, keywords were used to perform scanning between 18 February - 22 May 2021 to minimize skipping data. The main reason for choosing these databases is to reach as much data as possible without being dependent on any indexing. While the work done in the field of biomimicry in architecture was already limited, limiting it to indexing would greatly reduce the number of data to be included in the study.

During the initial scanning on Google Scholar, a total of 4950 results were found using the keywords "biomimetic" or "biomimicry" in all languages.

To reach the most accurate and comprehensive results about the use of biomimicry in the field of architecture from this wide scope, a limitation has been made in this framework. Although there was no resource and time limitation in the review, only English was reviewed to make the study universal. In addition, keywords only for determining the works in the field of architecture; review was done as "biomimetic" or "biomimicry" and "architecture" or "architecture design" or "sustainability". The filtering of the studies determined in line with the determined framework was done as seen in Table 2.

Table 2: Process of scanning academic studies (Cited from Halaç & Ergün, 2020)



In the first step, which is shown as the “definition” stage, the first filtering was made depending on the keyword and language selection, and a total of 258 studies were determined.

The identified 258 studies were subjected to 4-stage filtering in the screening section. These filters are sequentially;

- detected more than once in different searches,
- that were close to access,
- that were out of the scope of architecture,
- applied in architecture as those not related to biomimicry (Table 2).

Ten out of 258 academic studies found during the literature review had the same content but appeared differently; therefore, one of them was excluded from the scope. Among remaining 248 studies, 51 were close to access. Studies that could not be accessed were excluded. 63 of these studies were not included in the scope of the study because they were related to branches of science such as engineering and biology. 45 of the remaining 134 academic studies were not included in the scope of the study because they were outside the field of biomimicry in architecture. Consequently, 89 studies were included.

The remaining 89 studies’ details regarding “authors’ names”, “studies’ type”, “year of publication”, “the biomimicry subject reviewed in the relevant study”, and “purpose and methods” were obtained from every found study.

Data analysis was performed in two steps. In the first step, analysis of descriptive statistics was performed as “year of publication”, “country of preparing the publication” and “data type”. In the second step, the data were grouped according to the 5 dimensions of biomimicry determined by Zari (2007). As noted in Table 1, these dimensions are “form”, “material”, “process”, “structure” and “function”. Some data are gathered under the general heading of biomimicry because it covers more than one field. Data related to the use of biomimicry in architectural education were analyzed under the title of biomimicry in architectural education. The main reason for the separation of this group is that although it is not within the scope of the dimensions of biomimicry in architecture. It is related to the main purpose of this study. The research of biomimicry within the scope of architectural education will contribute to the awareness of students in this regard and to use it in building designs. After all the analysis, necessary lessons were learned and suggestions were made in this field (Table 4 - 5).

3. RESULTS AND EVALUATION

This section was examined under two sub-headings as “descriptive statistics” and “literature-based data analysis and assessment”. The section “descriptive statistics” presented the general numerical descriptions and assessments regarding the data included in the scope. The section “literature-based data analysis and assessment” presented the detailed review of 89 architectural studies.

3.1. Descriptive Statistics

Results indicated that the studies in the present research were conducted by the academics in 33 different countries, and only one study was conducted in 18 of these countries. The distribution of studies per countries (n=16) indicate that the highest number of studies were conducted by the academics in Egypt (18%) working in eight different universities (Figure 2).

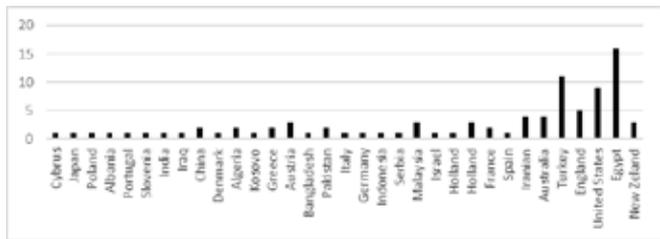


Figure 2: Distribution of studies per countries

In addition to Egypt; Iran and Malaysia, two Asian countries, had three (4.5%) and four (3.4%) studies, respectively. Furthermore, relevant studies were also found from the European countries such as Turkey (12.4%) and England (5.6%) and countries from Northern America such as USA (0.1%) and Canada (3.4%), suggesting that different architectural studies on mimicry were conducted in different parts of the world but few academics from a limited number of countries have focused on this topic.



Figure 3: Distribution of studies per continents

The fact that such studies have been carried out in countries with the highest energy consumption in Europe, Asia and North America may suggest that researchers in these countries are looking for building design methods that can reduce energy consumption (Akova, 2003).

According to research based on the Google scholar database, the first study on biomimicry in architecture was conducted in the USA in 1997 (Benyus, 1997). No relevant study that was conducted in ten years after 1997 was found, and three studies conducted between 2007 and 2010 were performed by Pedersen Zari (Zari, 2007, 2010; Zari & Storey, 2007). Other than them, the only study conducted in 2009 was performed in USA by Carro (2009), which suggests that biomimicry was studied by different academics from different regions after 2010. Year-based distribution graph suggests that the number of relevant studies increases particularly after 2011, supporting the aforementioned point. Analyses indicate that these studies were conducted the most in 2019 (%19.1). Considering these results, it is safe to state that biomimicry-related architectural studies have been increasing rapidly in recent years (Figure 4).

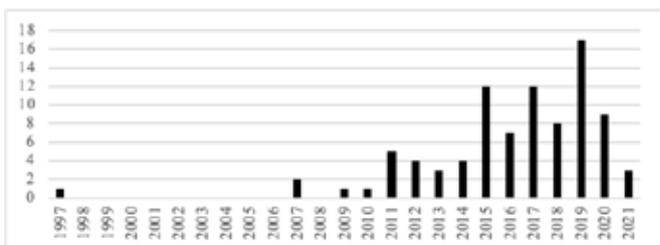


Figure 4: Distribution of studies per years

Nguyen et al. (2019) note that the use of local architecture in sustainability has been increasing since 2007. Comparison between the results of these two studies indicates that architects have been searching for different methods for sustainable building in recent years. It is clear that one of these methods is to be inspired by nature.

Most of the included studies were in the type of articles (44.94%; n=40), followed by full-text reports (34.83%; n=31) (Figure 5).

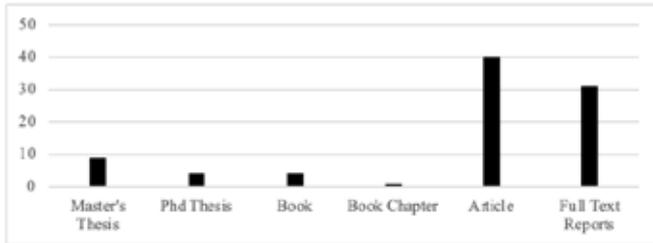


Figure 5: Distribution of studies per the data type

Analyses suggest that only two of the full text reports were presented in the same symposium, while the others were presented in separate symposiums. Only three of the articles in this study were published in the same journals. (Table 3). Among the remaining articles, two were from the same journals.

Table 3: Journals and symposiums with the highest number of studies on biomimicry

Renewable and Sustainable Energy Reviews	Al-Obaidi et al., 2017; López et al., 2017; Yuan et al., 2017
Architecture Research	Makram, 2019; Nkandu, 2018; M. M. Shahda, 2019
Architectural Science Review	Fecheyr-Lippens & Bhiwapurkar, 2017; Gamage & Hyde, 2012; Zari, 2010
Ecaade 2015: Real Time - Extending the Reach of Computation, Vol 2	Klemmt et al., 2015; S. Yazici, 2015

These results show that there is not enough scientific field about biomimicry in architecture. In addition, these results show that the number of studies and the importance given to biomimicry in architecture is still quite insufficient.

3.2. Literature-Based Data Analysis and Assessment

A total of 89 studies were grouped in two tables based on their scopes and purposes; “biomimicry dimensions” and “general frame of biomimicry” in the same table, and “biomimicry in architectural education” in the other. The section of biomimicry dimensions consists of five different groups: “form”, “material”, “process”, “structure” and “function”. These groups were formed based on the dimensions of biomimicry (Table 4 - 5).

Table 4: Grouping the studies based on biomimicry dimensions: form and material

Dimension	References	Author Name	Data Type	Objective	Method
FORM	(Mandee et al., 2021)	Mandee et al.	Full Text Report	To propose a nature-influenced building form performing minimum energy consumption in Al Basrah, Iraq	Simulation method (Quantitative method)
	(Kudumović et al., 2011)	Kudumović et al.	Full Text Report	To examine how the shell form can be used and modeled in architectural designing	Simulation method (Quantitative method)
	(Agirbas, 2019)	Agirbas	Full Text Report	To propose a ceramic form utilizing the influence of fractals in nature.	Simulation method (Quantitative method)
	(Le, 2020)	Le	Article	To determine the relationship between the fractals in nature and sustainable traditional buildings in Vietnam and to examine the impact of these fractals in the use of sustainable buildings in future	Simulation method (Quantitative method)
	(Colic-Damjanovic & Gadjanski, 2016)	Colic-Damjanovic, Gadjanski	Full Text Report	To explain the design and analyses of the form influenced by the nature while utilizing the digital application technologies of Fablab	Simulation method (Quantitative method)
	(Zulherman et al., 2019)	Zulherman et al.	Full Text Report	To examine facade designs for Lapau Panjang building considering the influence of nature	Field study (Quantitative method)
MATERIAL	(Xhexhi, 2020)	Xhexhi	Article	To explain the use of natural forms in architecture in time.	Historical research method (Qualitative method)
	(Nessim, 2015)	Nessim	Article	To propose a building envelope that is influenced by human skin ensuring heat control and that will reduce the energy consumption without using any electronic or mechanical material.	Simulation method (Quantitative method)
	(Achal et al., 2016)	Achal et al.	Article	To discuss the proposals regarding sustainable construction materials using the biomineralization technology considering the influence of nature.	Field study (Quantitative method)
	(B. Yazici & Gül, 2021)	Yazici & Gül	Article	To present acoustic metamaterial proposals considering the influence of nature.	Simulation method (Quantitative method)
	(Hershovich et al., 2021)	Hershovich et al.	Article	To present proposals based on facade coating materials with the influence of organisms' external forms to reduce energy consumption.	Field study and simulation method (Quantitative method)

Table 4: (Continuation) Grouping the studies based on biomimicry dimensions: process and structure

Dimension	References	Author	Data Type	Objective	Method
PROCESS	(López et al., 2017)	Lopez et al.	Article	To form a designing guide to adapt the working mechanism of plant leaves to building facades based on climatic characteristics in order to reduce energy consumption.	Field study and simulation method (Quantitative method)
	(Xing et al., 2018)	Xing et al.	Article	To present building envelope design proposals considering the working mechanism of plant cell walls.	Simulation method (Quantitative method)
	(Elghazi et al., 2017)	Elghazi et al.	Full Text Report	To present building facade design proposals considering the working mechanism of systems for the nastic movements.	Simulation method (Quantitative method)
	(Haque, 2019)	Haque	MA Thesis	To present roof system design proposals considering the influence of nature to ensure visual comfort and energy save in multi-purpose rooms	Simulation method (Quantitative method)
	(Nessim, 2016)	Nessim	PHD Thesis	To examine human skin for smart building envelope design that is lively and permeable and to adapt this design to architectural structure.	Experimental research method, field study and simulation method (Quantitative method)
STRUCTURE	(Sheikh & Asghar, 2019)	Sheikh, Asghar	Article	To present biomimetic facade design proposals by utilizing the structural form of oxalis oreghano leaves to improve the energy-efficiency of buildings with highly dynamic facades in hot and humid regions	Field study and simulation method (Quantitative method)
	(Al-Sehail, 2017)	Al-Sehail	Article	To determine the impact of master architecture designed considering the structural forms in the nature on vital sustainability.	Field study and observation (Mixed method)
	(Scuderi, 2015)	Scuderi	Article	To present proposals for conducting the rehabilitation of external building skeleton of social houses with the influence of nature in mind.	Field study (Quantitative method)
	(El Fattah, 2015)	El Fattah	MA Thesis	To present proposals for designing the load-bearing facade structure considering the similar function and influence of femur	Simulation method (Quantitative method)
	(Minsolmaz Yeler, 2015)	Minsolmaz Yeler	Article	To perform literature review for the buildings designed while considering the influence of natural organism structure.	Archive research method (Other method)
	(Klemmt et al., 2015)	Klemmt et al.	Full Text Report	To create an algorithm that serves as developing morphologies with architecture and is similar to the veins in leaves.	Experimental research method (Quantitative method)

Table 4: (Continuation) Grouping the studies based on biomimicry dimensions: function

Dimension	References	Author	Data Type	Objective	Method
FUNCTION	(Sara & Noureddine, 2015)	Sara, Noureddine	Full Text Report	To aim developing a new methodology considering the buildings designed with the influence of nature for energy-efficient building designs in warm and dry climates.	Qualitative research method (Qualitative method)
	(Chung, 2011)	Chung	PHD Thesis	To use biodynamics in architectural design considering the influence of nature.	Experimental research method and simulation method (Quantitative method)
	(Khelil & Zemmouri, 2019)	Khelil, Zemmouri	Article	To determine the use of nature-influenced technologies for a typical urban settlement in Southeast Algeria and to present designing proposals for passive ventilation and cooling system while implementing biomimicry principles.	Simulation method (Quantitative method)
	(Nalcaci & Nalcaci, 2020)	Nalcaci and Nalcaci	Full Text Report	To present facade design proposals that reduce energy use considering the adaptation of polar bear to external environment.	Simulation method (Quantitative method)
	(Fecheyr-Lippens & Bhiwapurkar, 2017)	Fecheyr-Lippens, Bhiwapurkar	Article	To design building envelope that reduces energy use after examining the biological characteristics of dynastes hercules and African reed frog.	Simulation method (Quantitative method)
	(Khosromanesh & Asefi, 2020)	Khosromanesh, Asefi	Article	To reduce energy consumption by presenting a proposal based on biokinetic building facade design that positions itself to sun and by examining ice plant seed.	Simulation method (Quantitative method)

Table 4: (Continuation) Studies on the general framework of biomimicry in architecture

Dimension	References	Author	Data Type	Objective	Method
GENERAL	(Makram & Ouf, 2019)	Makram, Ouf	Full Text Report	To examine the role of biomimicry and biophilia in forming a sustainable environment.	Archive research method (Other method)
	(Nkandu, 2018)	Nkandu	Article	To reveal the criteria of biomimicry based on sustainable building by analyzing three levels of biomimicry on five buildings.	Field study and observation (Mixed method)
	(Al-Obaidi et al., 2017)	Al-Obaidi et al.	Article	To ensure the development of sustainable facade designs through buildings with biomimetic facade designs considering the influence of nature and to provide solutions to technical problems.	Field study and archive research method (Mixed method)
	(Chayaamor-Heil & Hannachi-Belkadi, 2017)	Chayaamor-Heil et al.	Article	To increase researchers' awareness in terms of biomimetry by performing comparative analyses for nature-influenced buildings.	Simulation method and field study (Quantitative method)
	(Fahmy, 2018)	Fahmy	Full Text Report	To introduce biomimicry by reviewing the nature-influenced buildings.	Observation (Qualitative method)
	(Gamage & Hyde, 2012)	Gamage and Hyde	Article	To present optimal ecological model for sustainable building by examining the advantages of biomimicry and designing strategies.	Qualitative research method (Qualitative method)
	(Chayaamor-Heil, 2018)	Chayaamor-Heil	Full Text Report	To examine the impact of nature-influenced algorithms and digital advancements on biomimicry in architectural and urban design.	Field study and qualitative research method (Mixed method)
	(Clements-Croome, 2013)	Clements-Croome	Book section	To examine the methods of transferring to architecture by reviewing the characteristics of living beings and non-alive objects as well as their adaptation to their location.	Qualitative research method (Qualitative method)
	(Hu, 2017)	Hu	Full Text Report	To explain biomimicry through occupational practice and certain studies from the relevant field.	Archive research method (Other methods)
	(Poulsen Rydborg et al., 2019)	Poulsen et al.	Full Text Report	To explain the ecosystem level of biomimicry based on the ecosystem in oceanic climate and to take lessons for sustainable buildings.	Qualitative research method (Qualitative method)

Table 4: (Continuation) Studies on the general framework of biomimicry in architecture

Dimension	References	Author	Data Type	Objective	Method
GENERAL	(Bayhan & Karaca, 2019)	Bayhan, Karaca	Full Text Report	To guide researchers by performing SWOT analysis about biomimicry and kinetic architecture.	Qualitative research method (Qualitative method)
	(Kosanović et al., 2020)	Kosanovic et al.	Full Text Report	To present proposals about the use of biomimicry in architecture.	Qualitative research method (Qualitative method)
	(Kozlov, 2017)	Kozlov	Full Text Report	To determine the examples regarding the "history" of biomimicry, its basic theoretical and practical benefits and its potential practices in contemporary architectural design.	Archive research method and historical researches (Mixed method)
	(Feizabadi et al., 2012)	Feizabadi	Article	To determine the manners of using these organisms in contemporary architectural buildings influenced by natural organisms.	Archive research method and field study (Mixed method)
	(Fiorelli, 2017)	Fiorelli	Article	To determine the designing principles to be used for social isolation while considering the influence of insects.	Simulation method (Quantitative method)
	(Ibrahim, 2015)	Ibrahim	Article	To discover the use of nature in architecture for sustainable building and to analyze modern buildings in Egypt.	Field study and observation (Mixed method)
	(Abdelsabour, 2019)	Abdelsabour	Article	To assess the use of biomorphic design methodologies to form innovative structural forms, systems and construction methods considering the influence of nature.	Observation (Qualitative method)
	(Karabetça, 2015)	Karabetça	Full Text Report	To provide information about the use of biomimicry as a designing method in architecture	Qualitative research method (Qualitative method)
	(Abaeian et al., 2016)	Aaeian et al.	Article	To form a guide for researchers by determining the designing criteria for nature-influenced buildings to ensure thermal comfort in warm and dry climates	Qualitative research method (Qualitative method)
	(Ferwati et al., 2019)	Ferwati et al.	Article	To develop the frame of natural influence on designs at urban and building scale.	Field study and archive research method (Mixed method)

Table 4: (Continuation) Studies on the general framework of biomimicry in architecture

Dimension	References	Author	Data Type	Objective	Method
GENERAL	(Uchiyama et al., 2020)	Uchiyama et al.	Article	To guide the efforts of practicing by performing systematic review for the studies on biomimicry in architectural and urban design.	Archive research method (Other methods)
	(Januszkiewicz, 2019)	Januszkiewicz	Full Text Report	To present building design proposals that will reduce the impacts of climate change considering the influence of nature.	Simulation method (Quantitative method)
	(Saleh & Jaafar, 2020)	Saleh, Jaafar	Full Text Report	To reveal the role of natural organisms' growth characteristics in ensuring the functional development of architecture and environmental sustainability.	Simulation method (Quantitative methods)
	(Meriem & Mohamed, 2016)	Meriem, Mohamed	Full Text Report	To reflect the importance of digital technology in nature-based building designs and to provide a new biomimicry-based perspective to designers for sustainable building.	Qualitative research method (Mixed method)
	(Gamage & Hyde, 2011)	Gamage, Hyde	Full Text Report	To explain new environmental theories and designing approaches such as biomimicry that searches for ecological solutions by mimicking the forms, processes and ecosystems of nature for a sustainable building.	Qualitative research method (Qualitative method)
	(M. Shahda et al., 2014)	Shahda et al.	Article	To present proposals about the methodological frame of using the behavioral level of biomimicry in building designs.	Simulation method and field study (Quantitative method)
	(Gruber & Imhof, 2017)	Gruber, Imhof	Article	To present proposals with biomimicry-based designing approach utilizing the growth contact in biology.	Simulation method and experimental research method (Quantitative method)
	(Kokturk & Altun, 2018)	Kokturk, Altun	Book	To make a broad definition based on various perspectives about the use of biomimicry in architecture.	Simulation method and field study (Quantitative method)
	(Yuan et al., 2017)	Yuan et al.	Article	As a study based on the examination of bionic technologies for building functions, buildings and materials, to determine the designing criteria necessary for bionic-green architecture by analyzing the bionic building energy efficiency, bionic-green architectural practices and typical cases.	Qualitative research method (Qualitative method)

Table 4: (Continuation) Studies on the general framework of biomimicry in architecture

Dimension	References	Author	Data Type	Objective	Method
GENERAL	(B. V. D. Nguyen et al., 2018)	Nguyen et al.	Full Text Report	To present a digital-physical modeling aiming to explore the tectonic combination of origami folding patterns and micro-kinetic movements considering the influence of nature.	Simulation method (Quantitative method)
	(Garcia-Holguera et al., 2012)	Garcia-Holguera et al.	Full Text Report	To improve the use of ecosystem biomimicry using the ecological system diagrams.	Theoretical research method (Quantitative method)
	(Prakash & Sharma, 2017)	Prakash, Sharma	Article	To reveal the impact of biomimicry dimensions and principles on building sustainability through the buildings designed with the influence of nature.	Historical qualitative research method and field study (Mixed method)
	(Royall, 2013)	Royall	Article	To draw the outlines of a concrete theoretical and practical definition for biomimicry and examine architectural practices.	Field study and simulation analysis
	(Carro, 2009)	Carro	MA Thesis	To discover the organisms that can be added to the sustainable architecture in nature and re-interpreted.	Simulation method and field study (Quantitative method)
	(El Ahmar, 2011)	El Ahmar	MA Thesis	To establish a relationship between biomimicry and morphogenetically-calculated designing for a more sustainable architecture.	Field study and qualitative research method (Mixed method)
	(Nurbhai, 2015)	Nurbhai	MA Thesis	1. To determine whether the influence of natural forms and processes is adequate. 2. To reveal the biomimicry theories and practices in architecture using a philosophical perspective	Archive research method (Other methods)
	(Gruber et al., 2011)	Gruber et al.	Book	To provide extensive information about the use of nature in various scientific disciplines, particularly architecture.	Qualitative research method, simulation method and field study (Mixed method)
	(Gruber, 2014)	Gruber	Book	To provide extensive information about the use of biomimicry in architecture and to reveal its use in architecture throughout the history.	Historical researches and field study (Mixed method)
	(Chu, 2014)	Chu	PHD Thesis	To discover the place of nature in the design-based projects of R. Buckminster Fuller considering the influence of nature.	Simulation method and field study (Quantitative method)

Table 4: (Continuation) Studies on the general framework of biomimicry in architecture

Dimension	References	Author	Data Type	Objective	Method
GENERAL	(Gamage, 2015)	Gamage	PHD Thesis	To form a biomimicry approach within the eco-design practice by determining how biomimicry is conceptualized and used as a design-based approach in architectural eco-design practice.	Survey research method and archive research method (Mixed method)
	(Cruz, 2016)	Cruz	MA Thesis	To present a proper method proposal to determine the best biomimicry practices on the global scale and to ensure a sustainable building utilizing biomimicry.	Field study (Quantitative method)
	(Button, 2016)	Button	MA Thesis	To present examples about the use of plants, bacteria and other organisms for certain methods such as the collection of water, wind and solar energy and waste management, and to present proposals regarding their use in architecture.	Simulation method and field study (Quantitative method)
	(Ortiz, 2020)	Ortiz	MA Thesis	To group the names regarding the methods of using natural influence in architecture through different examples and based on the purposes of use.	Simulation method and theoretical research method (Quantitative method)
	(Pasic, 2014)	Pasic	MA Thesis	To examine the importance of using biology in architecture and the reasons for biology being integral to architecture.	Qualitative research method (Qualitative method)
	(Zari, 2007)	Zari	Full Text Report	To define the levels of biomimicry in architecture and the dimension at every level in a comprehensive manner.	Qualitative research method (Qualitative method)
	(Zari & Storey, 2007)	Zari, Storey	Article	To clarify different approaches regarding biomimicry in architecture and to present a series of principles that may constitute the basis of ecosystem-based biomimicry.	Qualitative research method (Qualitative method)
	(Benyus, 1997)	Benyus	Book	To create a guide about biomimicry as the common field of interest for different scientific disciplines.	Qualitative research method (Qualitative method)
	(Zari, 2010)	Zari	Article	To examine the ecosystem level of biomimicry as well as its use as an instrument to reduce the impacts of climate change and to increase the adaptation to these impacts.	Qualitative research method (Qualitative method)
	(Makram, 2019)	Makram	Article	To define the methods of being influenced by nature in architectural building design for a sustainable life.	Qualitative research method (Qualitative method)
	(Mohamed, 2018)	Mohamed	Article	To form face-based proposals that reduce energy consumption considering the influence of nature in the stage of designing building.	Field study and simulation method (Quantitative method)

Table 5: Biomimicry in architectural education

References	Author	Data Type	Objective	Method
(Omar et al., 2019)	Omar et al.	Full Text Report	To form the necessary criteria for adopting biomimicry within the education of architectural design.	Field study (Quantitative method)
(Amer, 2019)	Amer	Article	To show the importance and potential of biomimicry as a designing method on students' designs.	Survey researches method (Quantitative method)
(S. Yazici, 2015)	Yazici	Full Text Report	To assess an undergraduate elective course entitled "Sustainable Design and Environment Through Biomimicry" in the scope of biomimetic designing strategies and calculated design.	Field study (Quantitative method)
(Varinlioglu et al., 2018)	Varinlioglu et al.	Article	To increase students' power of designing with the nature-influenced digital designing instruments and to discuss the results that emerged within the studio course entitled "ARCH 202" aiming to teach new methods.	Field study and simulation method (Mixed method)
(M. M. Shahda, 2019)	Shahda	Article	To improve architecture students' skills of understanding buildings' structure using biomimicry.	Field study (Quantitative method)
(Stevens et al., 2020)	Stevens	Article	To determine the criteria necessary for increasing the levels of natural influence on students for more sustainable architectural building analyses.	Qualitative research method (Qualitative method)
(Dickinson, 2012)	Dickinson	Full Text Report	Using the connections between sustainability, biomimicry and digital technology, to explore sustainable skyscraper forms and building typologies within the course "Sustainable Skyscraper".	Simulation method and field study (Quantitative method)
(Tavsan et al., 2015)	Tavsan et al.	Full Text Report	To teach biomimicry method to students by mentioning the contributions of alive animals' characteristics to architectural building designs to ensure students develop different solutions with the influence of nature in mind.	Field study and qualitative method (Mixed method)
(Asghar & Naqvi, 2019)	Asghar, Naqvi	Article	To help students adopt the concept of biomimicry as well as digital approaches so that they can design more innovative architectural buildings.	Simulation method and field study (Quantitative method)

(Bakri et al., 2013)	Bakri et al.	Full Text Report	To teach biomimicry levels and define the potential of biomimicry in generating creative ideas.	Field study and simulation method (Quantitative method)
(Symeonidou, 2019)	Symeonidou	Article	Based on the results of different researches, to reveal the geometric principles behind natural buildings along with students and to determine the relevant challenges while performing calculations.	Simulation method (Quantitative method)

3.2.1. Analysis and assessment of studies per their purposes

Studies that have been reviewed, 56.17% (50/89) focused on the general frame of biomimicry while 31.46% (28/89) examined a certain dimension of biomimicry (form=7, material=4, process=5, structure=6 and function=6) (Table 4). The remaining 11 studies are related to the use of biomimicry in architecture education (Table 5).

Most of the studies on the form dimension of biomimicry in architecture have focused on designing the building envelope that will reduce the energy consumption of buildings to minimum (Le, 2020; Mandeel et al., 2021; Zulherman et al., 2019). Considering that one of the most important building elements affecting the sustainability of buildings is the building envelope it can be evaluated that designing a building form inspired by nature will make significant contributions to sustainability (El-Darwish & Gomaa, 2017). 75% of the studies on the material dimension of biomimicry are about energy conservation of materials to be used in buildings (Achal et al., 2016; Hershovich et al., 2021; Nessim, 2015). Considering the need to improve the insulation and air tightness of the outer shell of the building in order to reduce the energy consumption of the materials to be used, the importance of producing materials inspired by nature emerges. All of the studies on the process dimension of biomimicry in architecture, and about 60% of the studies on the structure dimension are about reducing energy consumption in building designs. These results show the importance of being inspired by the structure or working mechanisms of the objects in nature for sustainable building design in ensuring the sustainability of buildings. Approximately 50% (23/50) of the studies include more than one dimension of biomimicry aimed at building design inspired by nature. One of the most important common purpose of studies on biomimicry in architectural education is to raise awareness of students' design inspired by nature and to teach the relationship between biomimicry and sustainability (Asghar and Naqvi 2019; Bakri et al. 2013; Dickinson 2012; Tavsan et al. 2015).

Although the scope of the studies and the way of inspiration from nature are quite different from each other in the groupings, it seems that the main purpose of the general is sustainable building design. However, the fact that a significant part of the studies still focus on the definition of biomimicry shows that this method is still not fully understood.

3.2.2. Analysis and assessment of studies per their methods

The research method is the collection of methods used to determine, analyze and process the data regarding an academic study (Büyükoztürk et al., 2008). Research methods are basically divided into two: qualitative and quantitative. Method which qualitative and quantitative techniques are collectively used are known as mixed method. Other than these, archive research method as well as information and communication technologies can be defined as other

methods (Nguyen et al. 2019). Certain scientific people particularly grouped the methods utilized in architectural academic studies. Groat and Wang (2013) divided the researches into seven different groups: “historical”, “qualitative”, “correlation”, “experimental and semi-experimental”, “simulation”, “logical argumentation” and “field study”. “Historical”, “logical argumentation” and “qualitative researches” are qualitative methods, while “correlation” is a mixed method, and “field study”, “experimental and semi-experimental” and “simulation” researches are quantitative methods.

Methods of researches within the study were analyzed based on this grouping (Figure 6).

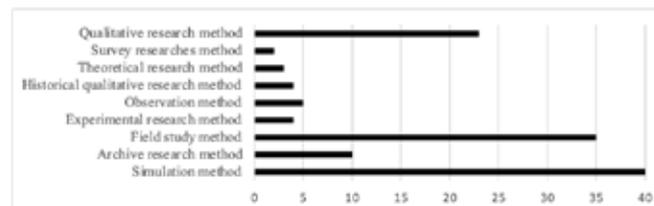


Figure 6: Distribution of research methods used in studies

Simulation method was used the most (32%; n=40) in the analyzed studies. These results support the idea that recent advancement in computer software has played an active role in the orientation of increase regarding biomimicry. Furthermore, 36% of studies utilized more than one method. “Simulation method”, “field study” and “qualitative methods” were used the most in studies (78%). These results indicate that both qualitative and quantitative methods were used in the architectural studies on biomimicry (Figure 7).

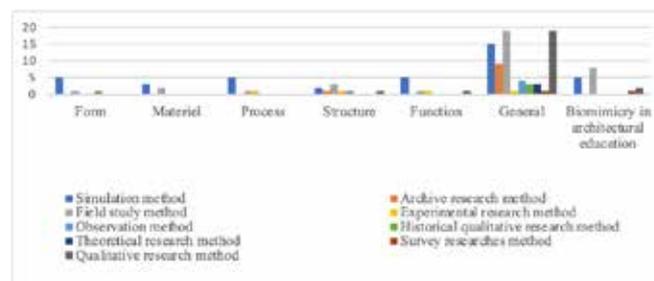


Figure 7: Distribution of studies per the research methods

The method is used in the biomimicry-related dimensions of architecture suggest that simulation method was used the most in 71% of the studies on “form” and “process”, 60% of the studies on “material” use, and 63% of the studies on “function”. 45% of the studies using the simulation technique aimed at sustainable building design. In the simulation technique, the geographical and climatic characteristics of a certain region can be prepared in the computer environment. Since the building can be designed in the virtual world before it is built in the real world, it can be designed to consume minimal energy. Therefore, the use of simulation technique can be recommended in studies aiming at sustainable building design. However, in the studies, the simulation technique was generally used together with the field study technique. Therefore, it suggests that using these two methods together can give the most accurate result.

4. DISCUSSION AND RECOMMENDATION

As a result of the analyzes and evaluations made, various suggestions are listed below for researchers who will work on the use of biomimicry in architecture and sustainability in the future. These are;

- energy consumption can be significantly reduced and energy production can be achieved by being inspired by the working mechanisms of materials in nature in building design. An example of this is the design of an energy efficient building by examining the orientation of the sunflower according to the angle of incidence of the sun. In cold climates, solar orientation can reduce energy consumption. In addition, energy production can be achieved by utilizing solar heat. This energy production can be achieved by the orientation of the photovoltaic panels according to the angle of incidence of the sun.
- by examining the protective layers of living things in nature, inspiration for the insulation of structures can be obtained. For example, the structure of the fat layer and feathers of polar bears living in very cold climates can be examined and adapted to the facade design. With the right analysis and adaptation, the formation of thermal bridges in the building envelope can be significantly prevented.
- by examining the skeletal system of living things, it can be adapted to the building structure of buildings. This adaptation will assist in structural analysis while improving the strength of structures. An example of this is the ability to cross large openings by examining the skeleton of a living thing.
- the energy efficient building envelope can be designed with inspiration from the working mechanisms of natural organisms. For example, the skins of cutaneous respiration organism creatures can be examined. This may contribute to the passive ventilation and lighting of the building.
- for sustainable building design, taking inspiration from nature, instead of just one feature of the organism, various features can be examined together. Because examining only one of these features may not be enough to reveal the real mystery in the natural adaptation of the organism.
- it can be suggested to use field study and simulation techniques together to design a sustainable building inspired by nature. It is thought that using these two techniques together will provide the most accurate result.
- in addition to such structural suggestions in energy-efficient building designs, it is necessary to raise awareness of architectural students in the field of biomimicry in architecture. Along with this awareness, the development of abilities related to being inspired by nature is also an important phenomenon for sustainable buildings. For the development of this awareness and skills, courses related to biomimicry in architecture should be added to the curriculum of graduate education, including undergraduate education in architecture. In addition, especially in undergraduate education, students should be encouraged to design projects inspired by nature.

5. CONCLUSION

The decrease in natural resources and the increase in energy consumption have increased the interest in sustainable building design. Biomimicry is one of the most important methods of sustainable building design. In this article, studies on the use of biomimicry in architecture are reviewed. As a result of the investigations, it has been determined that the inspiration from nature for sustainable building design can start from a single dimension of the organism level and more than one dimension can be investigated together at the ecosystem level. In addition, some studies encourage students, who are the architects of the future, to design sustainable buildings by creating awareness about the use of biomimicry in architecture. To reveal the mysteries of organisms or systems in nature or to raise awareness in this field, simulation technique and field study technique were used in general. Identifying the mystery of how organisms or systems adapt to nature is key to sustainable building design. Although studies in this area have increased in recent years, they are still insufficient. However, according to the analyzes made, the authors strongly believe that studies on the use of biomimicry in architectural building design will increase in the future. Bringing together and analyzing and evaluating the previous studies in this field is a guide for researchers.

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