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Bio-Mimicry in Architecture: An Explorative Review of Innovative Solution Toward Sustainable Buildings

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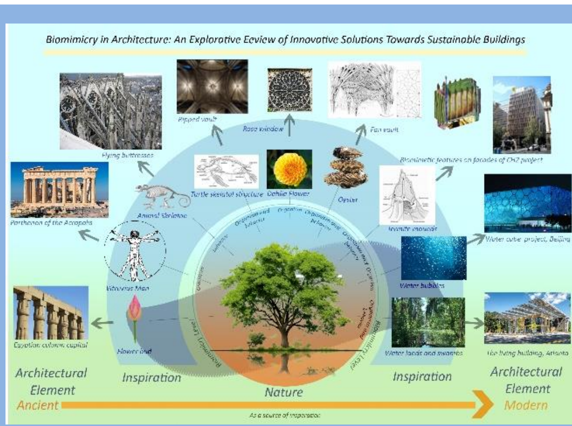
Abstract: Bio-mimicry is the imitation of the way nature solves problems. Architects and designers can utilize the ways nature follows to solve and address design problems. This science has helped humans in all life's aspects, especially in the field of architecture. From the dawn of history, people constructed special buildings to suit their needs. At first, the building process was hard, and the structure was simple and rigid with rough details and they kept repeating the same form. Therefore, architects have been searching for answers for their building complexes, and they found that nature was the best source of solutions. The structures then took different forms, were decorated with deep and graceful ornaments, the walls became thinner, more openings were constructed and the buildings became more beautiful and had more dignity. So, nature imitation has become the best approach for architects to deliver bold ideas to their surroundings. We can still see how the ancient unique buildings are standing still until this time, as in some Egyptian temples, Greek and Roman columns, and Byzantine ornaments. Imitation of nature in buildings is either through aesthetic, structural, or sustainability aspects. In this research, we are exploring the potential of Bio-mimicry to support sustainability, using a number of case studies throughout history, classifying and analyzing them.



Keywords: Biomimicry, Sustainability, Innovation, Gothic architecture, Contemporary architecture.

INTRODUCTION

Since the beginning of civilizations architects have tried hard to make their buildings beautiful, strong and functional.[1] However, with the development of building technologies, building materials and ways of living they realize that their buildings shall exceed these requirements to be in harmony with nature, make use of natural resources and forces, and be environmentally friendly.[2] These aspects in addition to others defined the sustainability of the building. The existing literature indicates a scarcity of studies delving into the role of biomimicry in offering innovative solutions for sustainable building. Consequently, this study aims to address this gap by examining and discussing the significance of biomimicry in sustainable construction practices.

Sustainable architecture

Sustainability is a societal goal that refers to people's ability to coexist safely on Earth for an extended period of time. "Sustainable architecture is an architecture that seeks to minimize the negative environmental impact of buildings through improved efficiency and moderation in the use of materials, energy, development space, and the ecosystem at large. Sustainable architecture uses a conscious approach to energy and ecological conservation in the design of the built environment."[3]

Overall, sustainable architecture is a set of building techniques that aims to reduce buildings' negative effects on nature and the ecosystem.

Biomimicry

Our universe has two creative forces: nature and mankind. Nature has its own perfect laws, which we can't change. Mankind in his creations may respect the laws of nature or may not. Respecting nature's laws doesn't limit humans' creative capacity, in fact, nature is a huge source of inspiration for designers and helps solve human problems [4]. From here, the term bio-mimicry has emerged, it is derived from: bios, meaning life, and mimesis, meaning to imitate.[5] The term bio-mimicry was coined by biologist Janine Benyus in 1997. It refers to a new scientific field that studies nature, its models, systems, processes, and elements, then imitates or takes creative inspiration from them to solve problems sustainably.[6] "Biomimicry encourages the transfer of functions, concepts, and strategies from natural organisms or systems to create a resilient built environment and improve its capacity for regenerative systems."[3] "biomimicry is interdisciplinary depends on understanding structure, functions, and principles of objects in nature to inspire design.[4]

Biomimicry in architecture

Biomimicry argues that nature is the most guaranteed and influencing source of innovation for designers and architects, due to nature's 3.85 billion years of evolution.[8] Therefore, the field of bio-mimicry is vastly expanding its domain in architecture as it encompasses the quest for innovative solutions. However, the idea of imitating nature was used centuries ago throughout history, though this term emerged in the 20th century, and became a hot topic of research in architecture and engineering.[3] This can be attributed to the fact that it is a source of inspiration as well as a method of creating a more sustainable and even regenerative built environment [9]. However, Biomimicry's widespread and practical application as a design method remains largely unrealized.

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Biomimetic architecture uses nature as an inspiration for both functional and aesthetical needs. For example, at the old temples of ancient Egypt, the columns were inspired by the lotus plant, a sacred plant for the ancient Egyptians.[10] Later in the Greek and Roman ages, trees and plants were a source of inspiration for ornaments in columns of the various classical orders, Corinthian and Composite orders were inspired by the Acanthus plant. Also, in Byzantine architecture, floral patterns were used to cover the plain structures.[11] Nowadays, modern sustainable architecture benefits a lot from nature [5]. In this research, we are going to focus on how nature inspired sustainable architects.

Bio-mimicry as a sustainable solution

Over time, energy around the world continues to decline against higher energy consumption in buildings, so architects are trying to find solutions to manage energy consumption in buildings.[12] They found that biomimicry is a solution based on adapting and extracting ideas from nature and incorporating them into our designs that help reduce environmental problems.[13] "When translating nature's strategies into the design, the science of the practice involves three essential elements: Emulate, Ethos, and (Re) Connect."[14] In the study of biomimicry, another three levels can be noticed:

1.Organism level 2. Behavior level 3. Ecosystem level.

The organism level shows mimicry of a particular organism or mimicry of a part of the whole organism.

The behavior level is the imitation of the behavior of the organism as a response to specific circumstances.

The Ecosystem level is to simulate the entire ecosystem. Most of the time sustainability can be expressed through this level.[15]

Through each level there are five dimensions that determine the extent to which imitation exists. Design is listed as biomimetic in the way it looks (shape), what it is made of (material), how it is made (construction), how it works (process) and what it is capable of (function)[16]. But not all levels can achieve sustainability. For example, designing a building in the shape of a cactus may not increase the overall sustainability of the building. Biomimicry provides a wide range of solutions for structural efficiency, water efficiency, zero waste systems, thermal environment, and energy supply, which are essential to any sustainable building design [17].

Literature Review

Many recent studies have focused on Biomimicry in architecture as a solution for sustainable buildings, such as Blanco. Et al. (2021) who discuss how ecosystem-level biomimicry can be applied to urban design to further integrate ecological knowledge into existing urban design frameworks through ecosystem biophysical structure. They emphasize the lack of integration in ecological theories and the narrow focus on energy and material. [18] Also, Verbrugghe, et al. (2023) highlights the need for a clear definition and understanding of the various approaches to bio-mimicry in architectural design and the gab was in a lack of generalized bio-mimicry methodologies [19]. Pedersen Zari (2018) addresses Embracing biomimetic principles, particularly in material selection and design, offers avenue for fostering sustainability in the face of climate change, utilizing carbon sequestration mechanisms found in living organisms and ecosystems. [20] In this research, there is a need for more experimental evidence in case studies which demonstrating the effectiveness of biomimetic approaches in addressing climate change in the built environment. Scott Turner (2008) gives A better understanding of the structure and function of termite mounds could lead to the development of new biomimetic building designs. [21] Gehan Radwan, et al. (2016) asserts that the building envelope is responsible for a significant amount of energy consumption, which can be reduced by identifying and mimicking nature's strategies. They used biomimicry to analyze case studies and their impact on reducing the energy consumption of the buildings. [22] Benyus & Janine M. (1997) explained the definition of biomimicry and how to apply this concept in different life aspects. [3] El Ahmar, S. (2011) investigates new strategies for sustainable design derived from the evolutionary development of living systems, through an attempt to link biomimicry and computational design, which is demonstrated in some case studies.[4] Moheb Sabry Aziz, Amr Y. El Sherif (2016) discussed how nature imitation helped designers to achieve the most efficient multifunctional structures and became the best approach for architecture and design to deliver bold ideas to their surroundings. [5] Ming Hu (2016) focused on the exploration of biomimicry's applications in structural design and addressed two important factors influencing structure performance: form-pattern making and the properties of materials, using numerous case studies to demonstrate different strategies corresponding to different levels of performance driven structure design based on bioengineering.[23] Rajshekhar Rao (2014) paper was about exploring the application of biomimicry in current architectural design, which would inspire architects to develop eco-performance principles that can be used to build biomimicry solutions to their designs.[24] Satu Niemi (2017) provided a definition and interpretation of biomimicry and a review on how biomimicry could be used in architecture, through analyzing some case studies that respond to the changes in the environment by emulating different adaptive strategies found in plants.[25] After reviewing these papers, we can conclude that the definition of biomimicry and its general applications were mentioned. Some papers linked this term to architecture and how to apply it on the aesthetical and structural aspects. Others dug deeper into how the application of biomimicry principles can be effective in the field of sustainable architecture and used some case studies to demonstrate. It was clear that the previous studies had made significant progress in exploring the utilization of bio-mimicry in architectural design, however there is still a clear gab that can be noticed in the formation of framework comprehensive enough to cover historical contexts. Here the aim of this study appears to address the gab by putting in record the application of bio-mimicry in architecture throughout history. Furthermore, our study identifies various approaches that can be used to apply bio-mimicry in sustainable architecture, clarifies them using comprehensive analysis of specific case studies, consequently enhancing the debate and move the understanding in the domain forward.

Research Question

This study is supposed to provide answers on how biomimicry provided a viable alternative approach to sustainable architecture?

RESEARCH AIM & OBJECTIVES

This study aims mainly at exploring the application of principles of nature in addressing sustainable architectural design challenges. It also explores the potential of emerging sciences in developing more livable and regenerative architectural solutions. The study additionally aims to provide an insight of the historical application of biomimicry in architecture, analyze the specific biological principles used and highlight their utilization in architectural practice.

METHODOLOGY

To achieve the aims of this study, we conducted a comprehensive tracking and analysis of bio-mimicry application in architecture through history by revision, exploration and classification of related successful cases in various civilizations. The selection of these cases was based on historical significance, relevance to contemporary architecture and availability of related data. We classified eight case studies to provide a comprehensive image of the application of biomimicry principles in architecture based on theories and classification of biomimicry. The time frame for this study started from the very beginning of the civilization 6th century BC. to the recent decade which can be noticed under the -Chronology of utilizing biomimicry in buildings through history- section, in which we explored and discussed the role of biomimicry in Greek, Roman, Gothic, renaissance and modern architecture. We also carried out a comparative analysis for the selected case studies that identifies levels and dimensions of biomimicry. This comparison tends to show the various methods of the application of biomimicry in architecture as well as it provides a deeper understanding of diverse approaches to bio-mimicry in the field across various civilizations, which ultimately contribute to identifying opportunities and challenges. Employing a comparative method in this study is supported by previous studies. For example, Benyus 1997 established a framework that identifies three levels of biomimicry, organism, behavior and ecosystem. This framework shows that a design can imitate specific features of an organism, simulate the behavior of an organism in its context, or copy the function of an integral ecosystem[3]. Additionally, Zari 2007 contributed to the expansion of classification dimensions of bio-mimicry especially for architectural applications, by introducing five aspects: form, material, construction, process and function. Taking these aspects into consideration will help architects in identifying various opportunities for utilizing bio-inspired design principles in architectural practice.[26] Moreover Othmani et al. showed in their study how biomimetic strategies can be incorporated across multiple levels and aspects in buildings. Their study discussed a case in which a building functions at both the ecosystem level and behavior level, by storing rain water and using solar panels for the ecosystem level and by considering careful orientation and natural ventilation for the function level.[27] Furthermore, we investigated the possibility of incorporating and correlating the selected biological principles applied in the case studies with sustainable architectural design by defining architectural elements used, their inspiration source, the aim of application, the biomimicry level which was applied and what was its outcome. This methodology allowed for systematic comparison and contrast of various biomimicry applications in architectural design, explaining the variance of strategies selected and their validity in fulfilling sustainable architectural design objectives.

Chronology of Utilizing Biomimicry in Buildings Throughout History

The term biomimicry is fairly recent, but it has been a concept for centuries because nature has always inspired humans.[3] From the 6th to the 1st centuries BC, Greek philosophers such as Pythagoras, Empedocles, Aristotle, and the Roman architect Vitruvius were among the first thinkers to be influenced by and learn from nature.[28] For example, Vitruvius was shown to be influenced by his theory of basing the rules of proportion on the proportions of the human body. This proportional conformity of architecture to the human form, or more generally to the rules of proportion to nature, became the cornerstone of classicism [29]. Classical architects imitated the shapes of plants and animals, such as the design of the Corinthian capital.[30] The design of the Corinthian capital is believed to have been inspired by the natural form of the acanthus plant, characterized by its elegant and leafy fronds [29].

Later in the Renaissance, the fifteenth century AD, Leonardo da Vinci (1452-1519) believed that nature was the key to solving human problems that he was approaching studying nature similar to biomimicry, so he studied the anatomy of animals and plants, and the behavior of birds [29]. In Gothic architecture buildings were designed using biomimetic principles as Gothic architecture was a dominant style in Europe from the late twelfth century to the sixteenth century, which will be discussed later. Architects found another way to understand nature as ways and analysis of growth and development. For example, the courage ideas of Frank Lloyd Wright and Le Corbusier. The last believed that "biology is the greatest word in architecture and planning", he utilized sun shading devices in his designs. [6] Which is inspired by the way that plants use shading to regulate temperature and light levels. The 1960s can also be seen as the precursor to the biomimicry movement as researchers began to explore the concept of bionics based on the application of biology in engineering and design that could create better and more sustainable solutions [7].

However, the term Biomimicry first appeared in 1982. In 1997, scientist and author Janine Benyus popularized the term biomimicry in her book Biomimicry: Innovation Inspired by Nature [31]. Some of key initiatives regarding bio-mimicry include:

- The Biomimicry Institute co-founded in 2005 as a non-profit organization based in Montana, USA.
- Biomimicry Design Challenge: A competition
- Ask Nature: considered the very first searchable digital library [31].

In this timeline, there have been many applications of biomimicry, some of which we will review in the following case studies.

Data Collection

To obtain a clear understanding of the application of biomimicry in architecture and the effect of this application in providing sustainable buildings, the following case Studies provide a clear idea how biomimicry is used as a source of inspiration and reference of solutions that could enhance the sustainability of architecture and add to its quality.

Biomimicry in Gothic Architecture:

a- Fan vault (Figure 1): Inspired by an oyster shape (Figure 2). These vaults are constructed by rips that take the shape of a cross network. They are supported by columns and enclosed by stained glass[11]. Creating spaces in this manner is not only aesthetically pleasing but results in excellent indoor environmental quality because of the proliferation of natural light and the potential for natural ventilation[32].

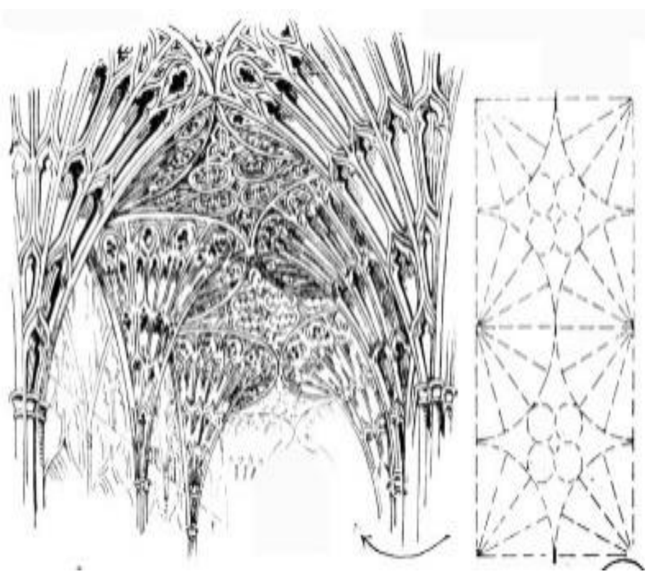


Figure (1): Fan vault [1].

Figure (2): Oyster [33].

b- Rose window (Figure 3): the gothic cathedral is known for its richly colored stained-glass windows and decorated interiors. The most iconic feature of the chapel is the western rose window, which details the Book of the Revelation of St. John. The design of the window resembles the Dahlia flower petals. "The light-diffusing and reflecting through hollow spaces in the vault, stained glass windows, and between the branching columns gives the effect of sunlight filtering through the leaves of a forest."[34]

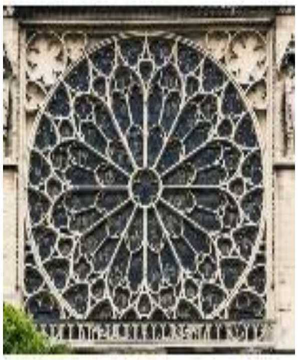


Figure (3): Rose window [35]

Figure (4): Dahlia flower [36]

c- An important feature of Gothic architecture was the flying buttress (Figure 5), a semi-arch outside the building that carried the weight of the roof or vaults inside over a roof or corridor to a heavy stone column.[37] Over time, the buttresses and pinnacles became more elaborate supporting statues and other decorations, as at Beauvais Cathedral and Reims Cathedral. The arches had an additional practical purpose; they contained lead channels which carried rainwater off the roof; it was expelled from the mouths of stone gargoyles (Figure 6) placed in rows on the buttresses. In a metaphorical comparison of an animal's skeleton with flying buttress.[38]

Figure (5): Flying buttresses [39].

Figure (6): Gargoyles [40].

d- Ribbed vault: Bearing a close resemblance with the skeletal structure of a turtle (Figure 8), In terms of shape and distribution of loads as well, “the design of these vaults evolved to bear the load of the structure through concentrated points throughout giving an impression of being on legs with counter thrusts provided by flying buttresses”[41] (Figure 7). A ribbed vault is considered a lightweight structure, through which the material used in construction can be reduced as in turtle skeletal structure (figure 8).

Figure (7): Ribbed vault [42]

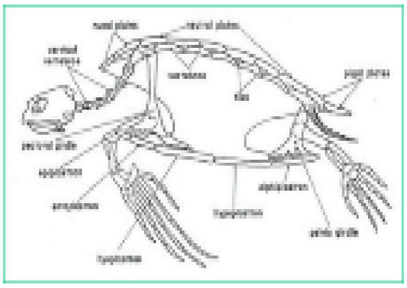


Figure (8): Turtle skeletal structure [43]

Bio-Mimicry in Contemporary Architecture:

As Architecture develops, Bio-mimicry has become a vital part of the architectural design process where architects and designers imitate nature to find innovative and sustainable solutions. This section explores a number of inspiring cases in which bio-mimicry in contemporary architecture has been applied.

Council House 2

Council House 2 (CH2) is a sustainable office building in Melbourne, Australia, that is often cited as a successful example of biomimicry in architecture, completed in 2006. The project took termite mounds as a source of Inspiration to provide a natural ventilation system; termite mounds regulate temperature and humidity. A system of chimneys and louvers was used at the building to attract from the bottom and release hot air at the top, resulting in a natural convection cycle. This system thus reduces the need for mechanical cooling and heating, and helps regulate temperatures and humidity levels in the building. The CH2 also includes a few of several other biomimetic features, including a facade that uses exterior vents to reduce solar heat gain and glare. The western facade represents the shell of the plant. The designer was inspired by the function of the façade of moderating the outdoor environment. While the north and south facades were inspired by the trachea of the tree. These worked as wind pipes and air ducts on the outside, the shell acting as a protective layer filtering light and air into the airy, humid area spaces behind. Finally, perforated metal with polycarbonate walls were added to the overlapping layers of the facade to hold the louvers as shown in (figure 10).[44]

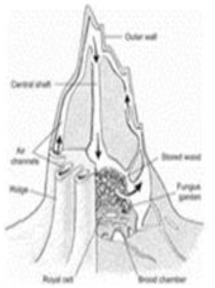


Figure (9): Termite mounds [44]

Figure (10): Biomimetic features on facades of CH2 project [44]

Water cube, Beijing

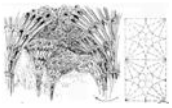
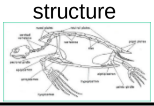
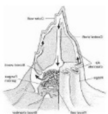
Water cube, Beijing also known as the National Aquatics Center, is a prominent building in Beijing, China, that was constructed for the 2008 Olympic Games after the winning of an architectural competition by CSCEC & PTW & ARUP to provide a unique project with maximum social and economic benefits[45]. Inspired by the structure of soap bubbles and the geometry of water molecules, both of which are patterns found in nature, they also represented the main ideal for swimming. The building's facade is made up of a series of translucent cushions, which are inflated with air and coated with a layer of ETFE, a transparent polymer that allows sunlight to pass through while insulating the interior. This system works on reducing the need for artificial lighting and air conditioning by providing natural light and ventilation. Water Cube Achieves sustainability through energy efficiency, isolating indoor and outdoor environment, providing design ideas of natural lighting resulted in reduction of energy and lighting coast by 30% while grabbing solar energy reduced lighting cost by 55%.[46]

The Eastgate Centre (1996, Zimbabwe)

The project is a good example that utilizes nature in architecture, one of the most effective solutions borrowed from nature is its passive cooling system that mimics the ventilation strategies of termite mounds. The

designers used a large central atrium which works as a lung that attracts in cool air at night and throughout hot one during daytime. Furthermore, the project utilizes maximum natural lighting to reduce dependence on artificial lighting through carefully studied orientation and the shape of the building. While shading devices protect the building from excessive heat gain and possible glare.

Table (1): Biomimicry in architecture.

	Element	Inspiration	Aim	Outc-omes	Biomimicry level
Gothic Architecture	Fan vault 	Oyster 	-Aesthetically pleasing -excellent indoor environmental quality	-----	Organism and behavior
	Rose window	Dahlia flower 	-Gives the effect of sunlight filtering through the leaves of a forest.	-----	Organism
	Flying buttress 	Animal skeleton 	-carry the weight of the roof	-----	Behavior
	Ribbed vault 	Turtle skeletal structure 	-Distribution of load	-----	Organism and behavior
Contemporary Architecture	**The Council House2** 	-Termite mounds  - Trees 	-Regulate temperature and humidity. -Reduce the need for mechanical heating and cooling. -The facades soften the outdoor climate.	-Air is 100% filtered. -Ventilation saved by 65%	Organism and behavior

	Element	Inspiration	Aim	Outc-omes	Biomimicry level
	Water cube[26] 	Water bubbles[26] 	-Provide natural light -Provide ventilation -Reduce the need for artificial light - Reduce the need for air conditioning	-Energy reduction 30% -Artificial lighting reduction 55%	Organism
	Eastgate Center [27] 	Termite mounds[27] 	-Natural ventilation -Natural lighting -Reduce energy use	The building use only 10% of the energy of a traditional building	Behavior
	The Living Building[28] 	Wetlands and swamps[28] 	Rainwater harvesting system	Reduce water consumption	Behavior

These strategies together with their careful application reduce the energy consumption to be 10% of that is needed for a conventional building. The building has also been provided with an innovative water harvesting and treatment system which is inspired from wetland and marshes, which work as a filtering and purifying device.[47]

Living Building at Georgia Tech (Kendeda Building)

The Living Building at Georgia Tech in Atlanta, Georgia, USA is a great example of how biomimicry has been incorporated into sustainable design. The building's rainwater harvesting system and water treatment process are based on natural systems such as wetlands and swamps, which function naturally. It naturally filters and purifies water. The collected rainwater is stored and treated using natural processes such as sand filters and plant-based systems. The building's green roof is another example of biomimicry, as it mimics the natural functions of a forest canopy by providing shade, regulating temperature and humidity, and providing a habitat for wildlife. A green roof works to reduce heat island effect on the building, which is a common problem in urban areas where buildings absorb and radiate heat, resulting in higher temperatures in the surrounding area [28]. The building uses solar panels on its roof and functions as both a water collecting system -infiltrate 15 times the amount of water needed by the building- and an electrical generating system generates 225 percent of the energy needed to operate the whole building [48].

RESULTS AND DISCUSSION

Mimicking nature has various levels including the organism level which is a part of the aesthetical aspect. the behavior level which helps achieve sustainability. and the ecosystem level which focuses on functional issues. The previous cases show that ancient Egyptians, Greeks and Romans copied natural plants as a part of their building's beauty. Goths on the other hand combined these two levels of biomimicry; the organism and the behavior levels. They built graceful buildings using elements that mimicked plants such as the rose window, and other elements that mimicked animals such as the flying buttresses and the ribbed vault. Nowadays, the field of biomimicry is having a high new level with the use of technology, and this will to a far degree improve buildings sustainably more than what was centuries ago. Currently, architects are focusing on solving certain problems, such as energy consumption, ventilation, heavy use of artificial lighting and lack of green spaces. That's why contemporary architects are also combining both the organism and the behavior levels of biomimicry and try to study and understand the ecosystem level to help them even more.

Referring to the reason for this paper which wonders how nature can help architects minimize their negative impacts on the environment, we can see that mimicking nature has provided many intelligent solutions. Applying biomimicry in buildings has infinite possibilities which of course produces different buildings with different solutions and impacts on sustainability. Mimicking in the organism level alone probably won't produce buildings with sustainable solutions, it should be combined with the behavior level or the ecosystem level.

In the Gothic period, biomimicry intended to create more graceful buildings with thinner walls and columns by reducing the amount of material used, and to solve the total load problems. (Table 1) above shows how Goths benefit from nature. In the 20th century when architects took biomimicry seriously, they started to see the great potential it has in solving human problems. By applying this science, architects build many great buildings with different inspirations for different purposes, and these buildings vary in the degree of sustainability that they reach, and that is shown in the contemporary cases mentioned above and are listed in (Table 1) above. Applying bio-mimicry as an architectural design method presents appropriate solutions to the current sustainability issues, and the cases previously discussed made it clear. Bio-mimicry has great potential in architecture, and it should be kept in mind that working with nature instead of against it will help both humans and the environment.

CONCLUSION

In conclusion this study has performed a careful exploration of the use of biomimicry in architectural design from the historical precedents to contemporary revolution. Using a systematic tracking and analysis of bio-mimetic case studies, that revealed valuable ideas from nature that inspired architectural design and demonstrated their contribution in providing sustainable solutions. The case studies which we discussed have not only shown the versatility of biological principles but also assured their capability for steering sustainable design practices.

Additionally, the investigation we did into the correlation between the biological principles and sustainable architectural design has shown promising applications for revolutionary future advancement in the field of sustainable architectural design.

In the end, Biomimicry is an emerging path in architecture from ancient times to the present day. However, the reason why biomimicry is not widely used in design is because the potential of bio-mimicry was not clear as today. To execute it on a grand scale successfully, there should be co-operation of multi-disciplines such as biology, ecology and design.

Steve Jobs was once quoted saying "I think the biggest innovations of the 21st Century will be at the intersection of biology and technology. A new era is beginning".

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- Consent for Publication: Not applicable
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