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The Role of Nature in Developing Sustainable Structural Systems for Architecture

Nour Mhammad Ahmad*, Omar H. Kharufa

Department of Architectural Engineering, College of Engineering, University of Mosul, Mosul 41002, Iraq

Corresponding Author Email: nour.20enp141@student.uomosul.edu.iq

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ABSTRACT

Nature serves as a strategy for achieving sustainability in architecture by reflecting the structural and aesthetic imagery inherent in natural systems and structures. Acting as a model and mentor, nature fosters innovative and sustainable designs. The aim of this research is to examine the role of nature in developing the architectural structure, which is a crucial element in achieving the desired integration of architectural components towards the goal of sustainability. Several structural variables influenced by environmental considerations emerge and ultimately shape the final design of the comprehensive structural system, bestowing unique characteristics to the architecture in one way or another. This research involves a review and discussion of a range of opinions and theoretical theses on the topic of nature's role in developing construction systems within a sustainable vision. This analysis is descriptive in nature, followed by a survey questionnaire for experts. The research highlights how considering structural efficiency to reduce energy consumption can lead to the creation of a more sustainable building through the influence of nature.

1. INTRODUCTION

Since antiquity, nature has served as a source of inspiration for architectural structures. This is evident in ancient Egyptian temples, for instance, where the design of temple columns was inspired by the lotus plant, and in the use of trees and plants as inspiration for decorative structural columns in the Greek and Roman classical era. The trend then shifted towards studying and emulating nature and its patterns to address the escalating human problems that accompanied technological advancement. Nature represented a reliable source for creating sustainable architecture due to its vast reservoir of solutions. At certain phases, architects such as Le Corbusier and Frank Lloyd Wright revolutionized traditional design styles with their bold ideas. Corbusier anticipated biology to be the most evident source of architecture, but their perspective of nature still lacked completeness. The biological metaphor was associated with the superior artistic imagery of nature's wonders and creatures, a notion clearly manifested in the buildings and products of the industrial era [1].

In the twentieth century, the focus shifted towards the principles governing biological forms rather than merely replicating them. Architects like Frei Otto and Buckminster Fuller began to seek the ideal structure in nature by mimicking the principles and strategies of biological systems. Fuller designed the geodesic dome, inspired by light and dynamic structural formations in nature [2], while Frei Otto approached the principles of structural design as not only a source of inspiration but also a means of learning construction techniques. For instance, his experiments with soap to create taut surfaces have become the primary contemporary reference for shell structures based on air and tensioned membranes [3].

Under the global changes and accompanying climatic repercussions, as well as resource scarcity due to man's misuse of the environment and the impact of lifestyle on the environment, architecture has emerged as one of the most impactful industrial environments affecting life and the surrounding ecosystem. Architects have increasingly turned to environmental design, which embodies the fusion of architecture and environment, and its influence on architectural formation. This approach views the building as an environmentally adaptive living organism, employing sustainability strategies in architectural formation and composition [4].

The concept of sustainability represents the optimal utilization of resources and capabilities in an effective, balanced manner, both environmentally and architecturally. It embodies the principle of meeting the needs of the present without compromising the ability of future generations to meet their own needs. Sustainable construction is a growing field and one way to address the phenomenon of global warming. Structural design can significantly impact the comprehensive sustainability of a building by considering the sustainability of the structure in relation to embodied energy of structural materials, design flexibility, deconstruction potential, and durability [5].

Modern technological developments have facilitated the exploration of architectural solutions, including utilitarian structural solutions, by creating a wide array of materials inspired by nature and applying them to architecture. With nature acting as a source of solutions in architecture through biomimicry, a building should represent an integrated and balanced part of the surrounding environment. The trend towards the biological nature, represented by the science of formation of living organisms, focuses on studying the structure, formation, and structural and tectonic arrangement of living organisms. This increases the designer's efficiency and ability to find balanced, adaptive, and environmentally

friendly design solutions [6].

From this perspective emerges the importance of simulating living systems in nature in terms of formation and structural composition as a means of achieving an architecture that is responsive to its environment. This serves as a sustainability-oriented approach by defining nature as a source of knowledge and inspiration to solve human problems [7].

2. RESEARCH PROBLEM

The research poses a query regarding how nature aids in realizing the concept of sustainability in architecture via structural systems. From this standpoint, the problem is defined as (elucidating strategies for capitalizing on nature to engender sustainable architecture through the structural system). In accordance, the research aspires to cultivate innovative design thinking that realizes a balanced and sustainable environment by transferring the traits of nature to architecture.

3. RESEARCH METHODOLOGY

In the theoretical aspect of the research, a descriptive and analytical approach will be adopted to clarify (the role of nature in developing structural systems to generate sustainable environmental architecture). This involves discussing and reviewing previous studies on the topic, followed by descriptive analysis to extract several vocabularies through which the role of nature in architecture can be realized, all in pursuit of achieving sustainability.

For the practical aspect of the research, the vocabularies of the theoretical framework (extracted from previous studies) were examined and tested by conducting a questionnaire to gather a summary of opinions from a select group of specialists regarding the impact of these vocabularies in achieving sustainable architectural structures. The samples included a select group of specialized academics with experience in the topic.

4. THE ROLE OF LIVING NATURE IN SUPPORTING ARCHITECTURAL AND ENVIRONMENTAL DESIGN

Nature is deemed one of the most significant sources of architectural inspiration and innovation, profoundly impacting architectural theories and practices. Innovative biological solutions have addressed architectural issues through strategies that seek sustainable solutions, contemplating how nature resolves its own challenges through innovative concepts and the use of intelligent materials. The aim is to find a solution to the world's environmental problems and identify optimal methods for integrating building design with the environmental system, rather than acting as an external factor contributing to environmental imbalance. Nature has provided solutions to many problems encountered by designers [8].

Studies indicate that many architects have drawn inspiration from nature for their designs. For example, Frank Lloyd Wright studied natural laws and extracted their structural composition, leading to several levels of nature imitation, including the formal pattern, behavioral, or environmental system level. Each of these levels can effectively address architectural and environmental issues. Knowledge has been transferred from biology to design-oriented disciplines such as architecture, either directly or indirectly, to solve design problems and develop functions, systems, and environmentally friendly solutions. The existing structures in nature stimulate architectural innovation functionally, aesthetically, and structurally [9].

Using structures similar to those found in nature may reduce energy consumption and stimulate the creation of structures with aesthetic and functional advantages. The emergence of effective and lightweight structural forms, the strategies, and solutions employed by nature, are a rich source of inspiration for various branches of science and technology. Biomimicry of nature offers a new approach to environmentally conscious building design that considers structural efficiency, energy efficiency, and water use, aiming to establish harmony between the building, land, and environment.

Nature has supplied a vast array of creatures whose structural and organizational characteristics can be studied to generate an architectural language that can be communicated through the spatial, formal, and structural aspects of architecture [10]. For instance, termite mounds have served as an ideal source of inspiration for developing more energy-efficient structures. Affected significantly by climate and soil conditions, termites constantly open and close a series of heating and cooling vents in the mound to regulate the building temperature throughout the day, as shown in Figure 1 (a).

A real-world example of this principle is the Eastgate Building, which operates similarly to termite mounds, as illustrated in Figure 1 (b). Outside air is drawn in through vertical ducts on the first floor, heated or cooled by the building's mass depending on which is hotter, then pushed up the building's floors via the central shaft before exiting through chimneys above [11]. Figure 2 illustrates air circulation in the Eastgate Building [12].

In the Eden Project located in England, the design of the building was inspired by soap bubbles, leading to the creation of a series of variable-diameter domes. The challenge in the building's design was to achieve a lightweight structure that consisted of multiple domes, each mimicking a specific biological environment containing a variety of plants from different parts of the world. The domes are composed of hundreds of hexagonal and some pentagonal sections, made of ETFE plastic.

a) b)

Figure 1. a): Air circulation in termite mound [12]; b) The Eastgate Centre, Harare, Zimbabwe [12]

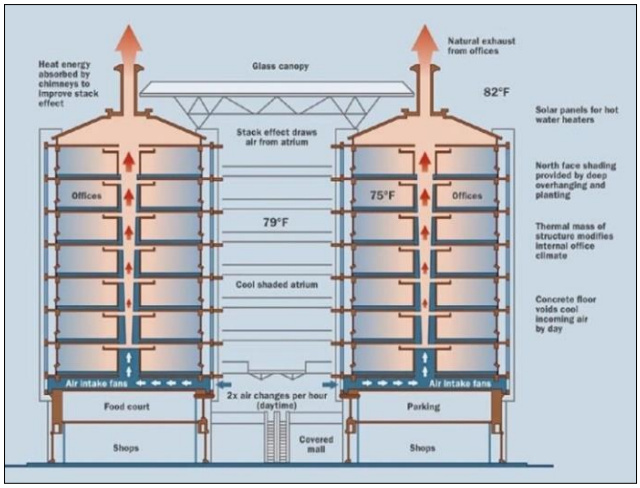

Figure 2. Air circulation in Eastgate Buildings

The project's needs required structures capable of establishing the appropriate environmental conditions to create an internal climate different from the prevailing local climate in the region. The geodesic dome emerged as a suitable and effective solution to this problem due to its ability to achieve the largest dome size with the least surface area.

The project consists of two enormous plastic houses, each composed of four interconnected domes, each forming a vital complex containing a controlled ecosystem [13]. This design can be seen in Figure 3 [14].

Figure 3. Eden project

Consider the Esplanade Theatre at Marina Bay in Singapore, a two-story structure designed to respond to its environment. The structure of the building envelope mimics the covering of the Durian fruit, serving as a protective layer for the fruit. The building's roof design consists of two circular structures equipped with triangular glass elements and sun canopies. The purpose of this design is to strike a balance between allowing outside views and controlling the amount of sunlight entering the building. These canopies are designed to provide additional protection to the structure from sun rays and thermal radiation [15], as illustrated in Figure 4 [16].

Thanks to advancements in technology, various architectural applications have emerged that are characterized by flexible, dynamic, and transformative structures. These advancements have a direct impact on architectural concepts and the emergence of new trends seeking solutions through the structural framework and the fusion of technology and science. Structures in responsive architecture strive to convert vital processes in nature and utilize them in engineering solutions, applying them to buildings.

Figure 4. Illustrates the Esplanade Theater project, inspired by the durian fruit

5. THE CONTRIBUTION OF LIVING NATURE TO THE DEVELOPMENT OF STRUCTURAL SYSTEMS IN ARCHITECTURE

Drawing inspiration from nature is a method of generating creative architectural ideas and achieving architecture that responds to its surrounding environment. It represents one of the successful solutions for sustainable environmental design using modern technology by adopting principles or behaviors found in nature that facilitate adaptation to the environment [17].

Architecture seeks to achieve structural optimization by enhancing the efficiency of an organism's structure or structural element. These elements are constrained by limited resources and environmental impact and demand lightweight, low-energy, high-performance structures in architecture. While the form used to solve the structure and the material, it has now become the effect of the structure, material, and function combined in determining the most efficient architectural form.

The trend towards environmental architecture in the current era has made nature a source of inspiration for structural ideas and principles. This is due to its ability to provide responsive and innovative solutions to architectural and structural issues and to achieve efficient and ideal structures. These structures illustrate the role of designs inspired by nature and reduce the environmental impacts of the building [9]. They seek structural forms using the principle of self-organization to use the minimum number of materials. Their beauty stems from their association with natural forms and their construction systems, leading to their utilization in architecture through the simulation of living nature in the formation of their constructing structure [18].

Shapes in nature bear similar characteristics in terms of their structural systems' ability to distribute forces and loads imposed on them and their resistance to lateral loads. However, they differ in terms of the external shape, which has proven its efficiency in withstanding changes in external environmental conditions in addition to its ability to adapt to it. This has positively reflected in its form and the emergence of structural systems that are inspired by living nature, such as shell structures, woven structures, tree structures, and deployable structures inspired by butterfly wings [13].

For instance, woven structures inspired by bird nests have

found application in the Beijing Olympic Stadium in China. The stadium has an oval shape and consists of a steel structure with a network of intertwined branches comprised of beams and columns interconnected with joints. The design of this network is inspired by bird nests [19], as seen in Figure 5 [20].

Figure 5. Shows the Beijing Olympic Stadium

Shell structures, particularly those inspired by crustaceans, are considered among the best examples of biomimicry. The concept of domes and shells was first developed by studying examples in nature and has contributed to achieving resource abundance. Pier Luigi Nervi frequently drew inspiration from nature to develop more efficient structures. A prime example is the Palazzetto dello Sport, which resembles the leaves of a giant water lily. The building is carried by the roof, which comprises a shell dome on Y-shaped columns, providing effective structural depth to a thin, flat surface [13]. This design is illustrated in Figure 6 [21, 22].

Figure 6. Palazzetto dello Sport project

Trees also contributed to the development of structural forms, as in the branching structural elements that were characterized by the use of tree-like columns, as the column rises from the ground with a full diameter like a tree trunk and begins to branch near the top to extend over a greater extent, as in the tree columns at Stuttgart Airport [19], as shown in the Figure 7 [23].

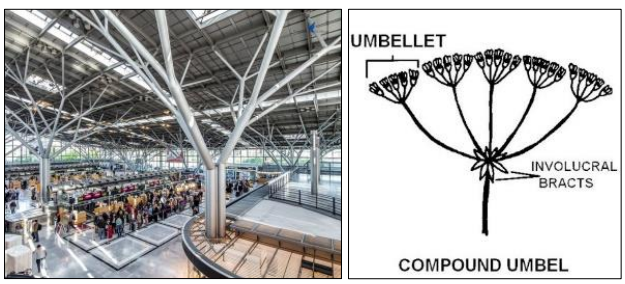

Figure 7. Tree columns at Stuttgart Airport

Nature has provided new and innovative possibilities and strategies that can be employed in architecture in terms of aesthetics and performance efficiency by using modern techniques, and methods and design based on digital technologies to achieve responsive architecture, as simulation of living systems emerged in terms of shape and structural composition as well as its contribution to the development of building materials and the creation of modern structural systems. There is no doubt that the tremendous development of digital technologies with all their programs, as well as the development in modern materials and manufacturing and implementation methods, has facilitated the design process and made it more flexible and creative. It has also become an important means that helps the designer in creating designs that have new and unexpected shapes, inspired by nature and liberated. From traditional design and construction constraints.

6. SUSTAINABILITY AND STRUCTURAL SYSTEMS

Sustainability is an environmental term and one of the design strategies that aim to reduce the negative environmental impact emanating from the built environment. Sustainable design aims to create living environments that minimize human use of materials and emissions from buildings, thereby reducing adverse impacts on the environment, health, and comfort of building occupants. This contributes to improving the building's performance. Nowadays, sustainability is a fundamental requirement in architectural design [24].

Sustainable building represents a growing area and a means of addressing the phenomenon of global warming. Structural design can significantly influence sustainability, as the sustainability of a structure can be considered in terms of the energy embodied in the structural materials, durability, flexibility, optimal design, and adaptability. Architects can reduce the embodied energy of the structural system by implementing principles of material reduction, flexible design, and demountable design. Choosing the right structural system can contribute to reducing energy consumption in a building's lifecycle and decreasing greenhouse gas emissions [5].

Structural sustainability refers to the development of structural systems to achieve integrated performance to meet new challenges and reduce the use of materials for sustainable solutions that fulfill human needs. Focus on sustainability in structural design has led to innovations in materials and the reuse of structural elements. Sustainable materials and integrated structures save energy and provide stability through new models for structural design and the selection of appropriate materials by turning to living nature [25].

The simulation of living nature has proven effective in achieving sustainability and improving efficiency in construction and design. Imitating nature in its forms, systems, and processes has contributed to solving the challenges our world faces. Nature's solutions assist in addressing our issues related to sustainable design [11].

Environmental architecture represents a contemporary philosophy that strives to find sustainable environmental solutions. This is achieved not only by simulating the structural form of living organisms but also by understanding the rules, principles, and behaviors governing these forms and the structural systems that provide flexibility and durability. Optimal structures use a minimum number of materials and are designed to adapt to the environment, thereby creating sustainable systems. This results in an integration between the structural system, architecture, and environment through design using modern constructional thought.

7. RELATED STUDIES

The role of nature in architecture has been evident since the inception of human construction. Nature was the first source of human creations, and its simulation has significantly influenced architectural and structural formation. This influence stems from researching the challenges of biological structural behavior and applying them to contemporary architectural designs. In contemporary architecture, inspiration from living nature focuses on morphological structures to achieve unique, sustainable architectural production capable of adapting to surrounding environmental conditions [15].

With the onset of the twenty-first century, interest in sustainable architecture emerged as a necessity for architectural development through biomimicry and recognizing nature as a source of inspiration for human problem-solving. In one study [26], researchers highlighted sustainable structures and strategies that assist in obtaining a sustainable structure. These strategies focus on structural elements and building materials and propose general guidelines for future structural design, such as flexibility, adaptability, and choosing systems that facilitate natural ventilation and lighting.

Another study [25] indicated that structural systems and their forms have evolved to meet new environmental challenges and to reduce material use by enhancing load-bearing abilities. This evolution has led to new formations. Achieving integration of structural systems with other architectural systems may not be suitable through traditional structural forms. Instead, it may require re-engineering structural shapes and systems and understanding how nature has developed sustainable structural solutions that have lasted for hundreds of years. These solutions emerged in response to external environmental conditions, which can help architects develop sustainable structural solutions that achieve energy-saving structural integration by thinking of new models for structural design.

One study [27] suggests that contemporary design greatly seeks to conserve materials in line with the idea of sustainable development. This includes searching for structural and architectural solutions through the concept of structural optimization, which is based on reducing material consumption. Structural solutions use genetic algorithms to improve structures and renew shapes, following a more advanced approach to reduce material consumption. This approach is similar to the concept found in nature: adding and subtracting materials where stress concentrates.

In another study [28], researchers highlighted the issue of high energy consumption in buildings and architects' attempts to find solutions to manage this problem. One innovative method is the imitation of living nature, which provides solutions to human problems through the study of systems, designs, and processes in nature. Depending on the surrounding environmental conditions, living organisms have developed their structures, which have become a source of inspiration for designers. This inspiration can be at the level of geometric patterns (like foam cells or bird nests), at the level of living organism behavior, or at the level of environmental systems in nature that focus on building performance such as natural ventilation and natural lighting. Architects turn to nature to achieve effective structures, similar to those found in natural systems, which focus on improving energy and material use.

From the aforementioned, it is clear that previous studies highlight the importance of environmental systems characterized by durability, sustainability, and efficient performance, in contrast to traditional linear systems. Structural systems in nature have contributed to the creation of sustainable, environmental architectural solutions that adapt to the needs of renewable life. This leads to an environmental design approach that facilitates harmony between the surrounding environment and architecture and relies on environmental and structural assessment standards to innovate successful solutions in architecture. However, these studies did not explicitly identify strategies for leveraging nature towards achieving sustainability in architectural structure.

Given this, the vocabulary extracted from the theoretical framework can be organized as shown in Table 1. This table illustrates the relationship of the theoretical framework's vocabulary to the degree of impact of living nature on structural systems.

Table 1. Variables of analysis

Studies	Variables	
[15]	Structural simulation	X_1
	Adaptation Structural	X_2
[26]	Structural flexibility	X3
	Sustainable response to the structure	X4
[27]	Structural innovation	X_5
	Structural optimization	X_6
[25]	Structural integration	X_7
	Structural form	X_8
[28]	Structural behaviour	X_9
	Structural transformation	X_{10}

8. APPLICATION

In the application, the vocabulary obtained from the theoretical framework and extracted from previous studies will be adopted for the purpose of exploring the impact of nature on architectural structures through what was proposed in these studies, and these vocabulary (X_1...X_{10}) will be adopted as independent variables that affect the extent of achieving Architectural structures for environmental sustainability.

On this basis, a questionnaire survey was conducted for academic experts who have experience on the subject to indicate some important aspects related to the application vocabulary by adopting a summary of opinions to explore the logical impact of nature in achieving sustainable architectural structures. The sample size was 70 respondents.

The questionnaire form included the sequence of vocabulary according to what appeared in previous studies for the purpose of answering a question posed to the questionnaire sample, which is (Does nature affect the achievement of architectural structures that respond to the environment and are compatible with the vocabulary presented for analysis), as a three-way Likert scale was used, and the questionnaire form included the possibility of marking (Agree, neutral, disagree).

9. THE QUESTIONNAIRE RESULTS

The results of the questionnaire were shown in the Table 2 as follows (Figures 8, 9):

Table 2. Sample questionnaire form

Variables	Repetition		
	Agree	Neutral	Disagree
X_1	40	20	10
X_2	40	30	0
X_3	50	20	0
X_4	30	30	10
X_5	30	40	0
X_6	40	30	0
X_7	70	0	0
X_8	60	0	10
X_9	20	30	20
X_{10}	0	60	10

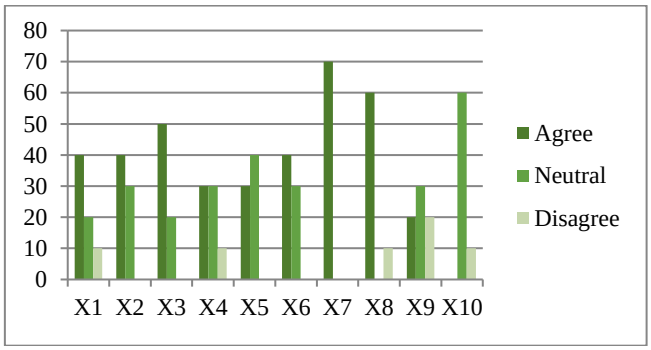

Figure 8. Histogram showing details Table 2

Figure 9. Diagram of the relationship of main variables to level importance

10. DISCUSSING THE RESULTS

The Table 2 highlighted the emergence of the application vocabulary according to the results extracted from the questionnaire in a way that shows the importance of these vocabulary as a summary of the opinions of specialists.

- On this basis, the structural integration variable (X_7) appears in the form of full agreement and (100%) of the questionnaire sample, which supports its importance in evaluating the environmental response of the structure.
- Also, the variable of the structural form (X_8) appears in the second place in terms of importance, with a percentage of (86%) in the form of agreement and a percentage of (14%) for disagreement with the absence of neutral answers.
- In the third place, the variable related to structural flexibility (X_3) came with a percentage of (71%) for the agreement formula with (29%) for the neutral formulas, and no formula was shown rejecting the effect of this variable.
- In the fourth place in variable of importance, the variables of Structural optimization (X_6), structural adaptation (X_2) and structural simulation (X1), respectively, at a rate of (57%) for approval formulas. While the neutral formulas for the two variables (X_6, X_2) came in the same percentage (43%) for each of them. As for the variable (X_1), the percentage of neutral was (29%) with a percentage (14%) of the rejection formula.
- And in the fifth place came the variables related to the sustainable response to the structure (X_4) and the structural innovation (X_5), respectively, with a percentage of (43%) for the approval formulas, with a percentage (43%) for the neutral formulas and (14%) for the rejection formulas for the variable. As for the variable (X_5), the percentage of neutral formulas was (57%). There were no dismissive formulas.
- And in the sixth place, the variable related to the structural behaviour (X_9) appears with a percentage of (29%) for the approval formulas and (29%) for the rejection formulas with (42%) for the neutral formulas
- And in the last place came the variable related to the structural transformation (X_{10}) that there were no forms of agreement with (87%) for the neutral formulas and (14%) for the rejection formulas.

Thus, the variables related to the impact of living nature on the structural systems to generate sustainable eco-architecture can be organized in the following way, as shown in Table 3.

Table 3. Arrange vocabulary according to level of importance

Variables		Vocabulary Explanation
1	X_7	Structural integration (Structure integration with other architecture systems and environmental considerations)
2	X_8	Structural form (origin design formally)
3	X_3	The possibility of modification to the structural system (structural flexibility)
4	X_6	Structural optimization (improve structural hardness indicators by using less materials)
	X_2	Adaptation Structural (considering the surrounding condition)
	X_1	Structural simulation (direct and indirect metaphor through biomimetics)
5	X_4	Sustainable response to the structure (successful reaction to changing conditions through time)
	X_5	Structural innovation (creating functionally and aesthetically efficient structures)
6	X_9	Structural behaviour (physical considerations of the structure for transmission of forces and load)
7	X_{10}	Structural transformation (change over time)

11. COMPARE THE STUDY RESULTS WITH PREVIOUS LITERATURE

Structural integration plays a crucial role in achieving sustainability by merging nature with the built environment. This has not been explicitly demonstrated in previous studies. Nature has also contributed to the creation of effective forms that display remarkable efficiency and offer a rich source of structural ideas. These ideas can potentially outperform traditional structural forms and effectively align with existing advancements in nature. This creates new sustainable standards that make our built environment more robust and sustainable, which aligns with what previous studies have indicated.

Structural flexibility is considered an important factor in accommodating any future modifications at the functional level. This mirrors nature's ability to solve design problems efficiently and creatively, a topic that previous studies have addressed to a certain extent.

Regarding structural improvement, this emerges from nature's principles of using the minimal amount of materials to achieve the maximum effect and structural efficiency. However, this concept has not been clearly demonstrated in previous studies.

Furthermore, structural innovation results from sustainable formulas in structure and contributes to creating new sustainable structure types. This aspect has not been clearly addressed in previous studies either.

12. CONCLUSIONS

- The importance of structural integration has emerged, which demonstrates the interaction of the structure positively with the surrounding physical environment, given that this aspect has an effective impact in evaluating the extent of the success of architecture locally and comprehensively, as it is an integrated system that cannot be separated from its neighbourhood, as nature is a rich source of formations, systems and resources that can be utilized in. Architecture is like structures and materials, which, when integrated together, create an effective and more efficient system.
- The formal design of the structure is an important factor in determining the environmental response of the structure, given that the formal configuration, whatever its details, must overlap with the surrounding environmental considerations in form and content (such as the influence of wind, etc.) and is considered one of the most important design treatments that aim to resist climatic conditions.
- Regarding the sustainability of the structure, the successful response to changing conditions over time is important in indicating the level of environmental response of the structure, given that the environmental aspect is one of the pillars of achieving sustainability at all levels. Attention must also be paid to the necessity of adopting renewable structures (structural innovation to achieve the best interactions with the environment). Structural design has a significant impact on the overall sustainability of the building by applying the principles of reducing materials, moving towards flexible design, and choosing a system that contributes to reducing energy consumption.

13. RECOMMENDATIONS

- Innovation new structural forms with a sustainable natural reference (in terms of flexibility in simulating their elements and streamlining formations, as well as their working mechanism).
- Expanding the design horizons of architects towards sustainable derivation from nature.
- The research recommends the importance of adopting structures found in nature in contemporary architecture because they are more efficient and contribute to creating environmental architecture that is responsive to external and internal conditions and influences and contributes to achieving sustainability.
- Working to encourage architects to benefit from nature and its systems and try to integrate them with architectural systems, taking into account reducing the consumption of energy and materials and reducing the effects of construction on the natural environment.

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