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Review

Biomimicry and the Built Environment, Learning from Nature's Solutions

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Abstract: The growing interest in biomimicry in built environments highlights the awareness raised among designers on the potentials nature offers to human and system function improvements. Biomimicry has been widely utilized in advanced material technology. However, its potential in sustainable architecture and construction has yet to be discussed in depth. Thus, this study offers a comprehensive review of the use of biomimicry in architecture and structural engineering. It also reviews the methods in which biomimicry assists in achieving efficient, sustainable built environments. The first part of this review paper introduces the concept of biomimicry historically and practically, discusses the use of biomimicry in design and architecture, provides a comprehensive overview of the potential and benefits of biomimicry in architecture, and explores how biomimicry can be utilized in building envelops. Then, in the second part, the integration of biomimicry in structural engineering and construction is thoroughly explained through several case studies. Finally, biomimicry in architectural and structural design of built environments in creating climate-sensitive and energy-efficient design is explained.

Keywords: biomimicry; architecture; structural engineering; sustainable design

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1. Introduction

Biomimicry is the design that is inspired by nature in terms of functional concepts of an organism or an ecosystem [1]. According to Janine Benyus, bio-mimicry mimics processes in nature to create innovative and sustainable design solutions [2]. She also describes biomimicry as a science in which nature is considered the mentor and model for design [2,3]. In general, biomimicry uses ecological benchmarks to assess sustainability and create vernacular designs inspired by nature in terms of form, process, and ecosystems [2]. Other scholars have perceived biomimicry as a field of science that aims to address human needs through mimicking natural designs, processes, and systems [4,5]. Biomimicry is a multidisciplinary field of research where experts with diverse backgrounds (e.g., philosophy, computer science, physics, and chemistry) work together with biologists and engineers to create highly resilient products. Biomimicry is quite critical for today's world, where rapid climate change and environmental degradations occur.

Historically, the art of biomimicry goes back to 500 B.C., when Greek philosophers learned from the natural organisms and applied their mechanisms, shapes, and functions as the model to make the balance between different parts of design and create the classical idea of beauty [6]. Later, in 1482, Leonardo Da Vinci invented the flying machine by studying the mechanism of birds flying and labeled his work as the early example of biomimicry [6]. Although he was unsuccessful with the flying machine, his invention later led to the development of Wright's brother's prototype to an airplane in 1948 [7]. In 1958, the term bionics was first introduced and defined as 'the science of natural systems or their analogs'. However, the term biomimicry did not appear before 1982. Later, in 1997, Janine Benyus expanded the concept of biomimicry in her book 'Biomimicry: Innovation inspired by Nature'. Then, she established the Biomimicry Institute with Schwan. In 2007, Chris

Allen joined the company to launch 'Ask Nature', known as the world's first digital library, which gives natural solutions and inspirations to design practice and research.

Biomimicry is different from bionic. Bionics is the design of engineering systems, especially electronic ones, based on biological systems, whereas biomimetic is the study of the structure and function of living things as models for creating materials or products by reverse engineering [8]. The act of studying and mimicking nature to come out with practical solutions that address human needs is not a novel practice. In the past, people were often inspired by nature to provide their food, shelter, and innovative methods to survive in harsh environments. These innovative methods have been re-used in the contemporary era in the fields of built environment, medical science, defense, agriculture, and even manufacturing processes [8–10].

The ecosystem and nature can be mimicked and contribute to the resilient, sustainable, and adaptable built environment, which improves the capacity of regeneration in the natural environment and adaptation against climate change [11]. Biomimicry also offers thoughtful solutions for human needs through a translational process into a human context where the design may not be similar to the source organism/ecosystem but poses the same functional concepts.

Early scientists have conducted in-depth studies on the functions and processes in nature. They have collected valuable information used in different areas of study, particularly design, architecture, and structural engineering. Thus, this study aims to review the use of biomimicry in architecture and structural engineering and investigates how biomimicry contributes to a sustainable and resilient built environment.

2. Biomimicry in Architecture

2.1. Concept of Biomimicry in Design and Architecture

According to Feuerstein and Fred Otto [12,13] biology and architecture are prerequisites of each other. Bioinspiration in architecture is understood as a practical methodology for answering the stakes of designs of forms and energy-efficient structures at the urban scale using natural materials. Biomimetic architecture aims to measure and shape space and to create synergistic relations between the environment and the structure.

The adaptability of nature toward different environmental changes has been well reported in the literature. This adaptability of nature has inspired several designers to create highly resilient and environmentally sustainable built environments [14]. This inspiration from nature has evolved in two ways in the context of design and architecture: direct and indirect approaches. Scholars [15–18] have comprehensively studied the features and characteristics of each approach in the work of well-known architects and designers.

The direct design approach occurs when a design directly copies an organism in the ecosystem and mimics its behavioral pattern or natural system. Whereas, the indirect approach solely uses abstract concepts in nature and employs them in design [19,20]. The direct design approach has two derivations with two diverse schools of thought and methods. The first approach understands the design problems based on a 'design exploring biology' concept, and the second approach explores the design issues from a 'biology investigating design' perspective [15]. The latter consists of identifying the human needs or design issues through understanding the processes that the ecosystems utilize to overcome such challenges.

In architecture, Biomimicry is also known for its problem-driven or solution-driven approach to architectural design issues [17]. In this approach, the designer explores solutions to address the problems through biology, whereas in the solution-driven approach biology is used as a solution to copy and then transfer to design systems.

Biomimicry inspires architecture in three ways; organism (imitation of nature), behavior (imitation of natural processes), and ecosystem levels (imitation of the working principles of ecosystems) [15]. At the organism level, design and architecture are mainly inspired by the form, shape, or structure of a building. At the behavioral level, the interaction between the ecosystem and its surroundings inspires the design. At the ecosystem level, the main focus is on how different parts of an organism interact on a large (urban) scale. Table 1 summarises the characteristics of each level. This approach has been methodized to apply to a design or an architectural problem [21].

Table 1. Framework for different levels of biomimicry.

Organism Level	Behaviour Level	Ecosystem Level
Mimicry of a specific organism	Mimicry of the way that organs behave of a larger context	Mimicry of an ecosystem

These levels have been thoroughly explained by Benyus through an example of an owl's feather. A feather can be renewed by its formal attributes. However, this replication cannot be considered a resilient and sustainable solution [2]. When the process is mimicked, identifying how the feather is produced without using toxic waste or a high level of energy consumption is feasible—realizing that how it impacts body heat and energy conservation and thereby achieves the properties of the feather is possible. At the ecosystem level, the existence of the bird and its feather with a larger biosphere and the entire organism is studied.

Each of these levels offers five potential dimensions to biomimicry: (1) how the design mimics the look and form of an ecosystem, (2) how it mimics the material of an ecosystem, (3) how it mimics the way that the ecosystem is being constructed, (4) how the ecosystem works (process) and (5) what the ecosystem is capable of doing (function). These levels are often used as benchmarks for architects to employ bio-mimicry principles in design and architecture approaches and create sustainable, efficient, and environmentally sound buildings.

In some architecture and design concepts, most projects are inspired by the form and behavior of certain animals (animals in the ocean or on the earth) that have adaptive approaches towards the outside world (e.g., sun and wind). In other architectural projects, the source of inspiration is plants that react differently towards extreme climatic conditions (drought, heat, and light).

2.2. Potentials and Benefits of Biomimicry in Architecture and Design

As discussed, biomimicry brings several inspirations from nature and introduces great potentials to create a sustainable, energy-efficient built environment. This great opportunity is more tangible, particularly today, because new building materials and new construction techniques can be seen more than ever in the past. However, the method in which the built environment reaches its final form is crucial. Therefore, the significance of a well-designed built environment lies in integrating creative processes learned from nature (biomimicry) and the wealth of knowledge in technology and tools. Therefore, the next sections of this paper provide an overview of the potential use of biomimicry in architecture.

2.2.1. Wise Selection of Construction Materials

Function

Wise material selection with a high level of functionality is one of the major benefits of applying biomimicry in architecture. The importance of understanding complex systems results in consideration of the individual aspects, which leads to an improved understanding of the overall function.

In nature, efficient materials are defined as those that have effective exchange with expensive materials (which are generated from metabolic processes). Nature has created sustainable light shell and fold structures and systems that can grow and be stable. Natural systems established the building processes in both animals and plants. This building process considers the availability of local materials and aims to create an optimized and multi-functional structure. Examples of such building processes can be seen in shell structures of mussels and sea and folded structures of leaves, hornbeam, and palm varieties.

Lifecycle

The life cycle is another great lesson learned from nature and be is implemented in architecture, whether the matured structures are occupied by new life forms or decomposed into basic elements, from which new life forms can emerge. Biomimicry in architecture has resulted in building materials and elements that can integrate themselves with a life cycle in nature. However, a tangible gap has been observed in the literature on how the life cycle of built environments can learn lessons from the natural processes and ecosystems in nature [22,23].

Weight

The concept of lightweight structures is another potential brought by biomimicry in architecture and building methods. Natural structures react to internal and external loads differently. Thus, their forms are affected by such factors, which is also the case for human-made technology-driven built environments. One of the benefits of using lightweight materials for building envelopes is the high level of insulation and light penetration, diffusion. An example of these features in nature can be seen in polar bear fur. It provides good insulation for the cold weather of Antarctica and allows the penetration of light into the darkly pigmented skin of the bear [24]. Another similarity can be seen between the hairs and parallel glass fibers, acting as the insulator and light distributor [25].

2.2.2. Structure Behaviour

The possibility of creating an evolutionary and evolving urban planning and design is another inspiration brought by biomimicry in architecture and design. The opportunity of using advanced and technology-driven tools enables the designers to choose the processes that are similar to those in nature and ecosystems. One of the pioneering institutions in using computer-/technology-supported algorithms for evolutionary urban design and urban planning is the Institute for Computer-Based Design at the University of Stuttgart in Germany. In one of the projects conducted by this institution, the structure of a building was thoroughly analyzed and optimized to improve the Structure's behavior, function, and, in certain circumstances, its mobility [26].

2.2.3. Building Envelope (Heating, Cooling, and Lighting)

There are infinite sources of inspiration from nature that can be utilized in different design and construction technologies and contribute to the effective algorithm, method, material, processes, structure, tool, mechanism, and systems. Living organisms have unique integration geometries and techniques that enable them to adapt themselves to harsh-diverse environments easily. Similarly, buildings nowadays use specific methods to adapt well to their surrounding environments and minimize the adverse impact on the environment.

Designing the building envelope is among the important methods. The building envelope, also known as the third skin, is 'an extended buffer between the building and the exterior environment'. The first human shelters and settlements consisted of cloths or natural caves. Later, these shelters were built with raw materials, and nowadays, we see communities where houses are built to protect one another and thus create a single unit with an external wall. However, with the development of individual buildings, the optimized envelop design and multi-layered construction have increased. Past services were mainly attached to the envelope and provided isolated solutions while neglecting the building features and improving the constant need for maintenance.

2.2.4. Building Facades

The biomimicry approach is not about copying nature in form but also learning from its principles and methods and coming up with sophisticated technological solutions for efficient building envelopes. One of these technologies is the techniques applied in building skin.

Building skin is a thin membrane that comes on top of the structure and regulates the mechanical and electrical function of the structure that also forms the buildings' interior spaces. There is a similarity between building skin as what we know as façade and natural skin in nature. Both consist of diverse layers that filter external newcomers and react differently to heat, pollution, water, and noise pollution. One of the main overlaps between these two types of skins is that both keep the condition of internal spaces constant while meeting the functional need of the space. They both act as a filter in the process of determining what is allowed to enter and exit [27].

The main benefit of utilizing biomimicry is that designing building skins creates an efficient thermoregulatory mechanism (such as heating, cooling, and lighting). To create a nexus between building skin and biomimicry, we need first to analyze the commonalities between the living ecosystems and building facades and the driving forces that influence the nature and design process. One of these similarities is the tendency of living organisms to adapt their temperature to their surrounding environments and maintain a steady condition. Similarly, animals constantly modify their structures and behaviors to maximize the use of available accessible sources of energy (e.g., wind, sun, and water).

2.2.5. Heating and Insulation

Similar to built environments, in ecosystems, heat is transferred through radiation, evaporation, conduction, and convection. In some animals, heat is generated inside the body, and the body then tends to keep the temperature steady. Whereas, in other types, heat is mainly absorbed from the environment, and the body temperature ranges quite significantly. The first type of animal and the concept of generating the heat from metabolism has been the idea behind heating techniques in many buildings. In this type of buildings, the spaces are kept warm by preventing heat loss. Therefore, insulation plays a critical role in addressing this objective. Polar bears in the Antarctic, and their bodies are the best examples of such adaptation capabilities. Layers of fat and a denser layer of fur act as insulation. Their hollow hair fiber adds to insulation strength. Similarly, in other animals, hair filaments conduct sunlight down to their dark skin to create a curtain wall system that automatically modifies their insulations.

2.2.6. Direct Heat Gain

Another method in keeping the space warm is through direct heat gain from the sun. Communal nests built from the silk layers that are oriented towards the southeast to capture the heat from the sun are a good example of this method. In this method combined effect of insulation and solar orientation can lead to a 4 °C higher temperature [28].

An example is how penguins create heat. Penguins live in groups, and their skins have a constant temperature, regardless of the ambient temperature around them. Penguins huddle in groups to reduce the exposure of their surfaces towards outside areas. A similar design principle can be seen in vernacular architecture where buildings link to each other, and the only open space is the atrium-shaped opening, which is mainly used for ventilation purposes (and often closed in winter to decrease heat loss).

Reducing heat loss from buildings would result in warmer indoor temperatures. Several passive Haus projects have adopted this concept where the heating system is mainly relying on the internal heat gains obtained from the metabolisms of the occupants and equipment in the building. One of the built examples of this biomimetic principle can be seen in the Himalayan rhubarb towers, where a vertical greenhouse of translucent leaves contributed to a 10 °C higher temperature in indoor spaces compared with outdoor ambient air temperature [29] to balance heat loss through the skin.

2.2.7. Cooling

Some living organisms that live in extremely hot regions avoid radiative heat gain by staying out from the sun or relieving from conductive heat gain by minimizing their skin exposure to the sun (skipping across the sand). This principle (avoiding direct heat gain) has become the main action plan in architecture for cooling buildings. This principle seems straightforward. However, its importance has not been highlighted till the late 20th century. A similar approach in architecture and design can be found in Cabo Llanos Tower in Santa Cruz de Tenerife, Spain by Foreign Office Architects and the Singapore Arts Centre by Michael Wilford and Partners with Atelier One and Atelier Ten

Another example is the work of Chuck Hoberman [30], who is also one of the pioneers in adaptive approaches towards solar shading. One example where a shading device is integrated into the building body is Hoberman's dynamic windows for The State University of New York's Simon Centre for Geometry and Physics (Figure 1). The windows function as the artistic centerpiece of the building and the functional shading piece. Every project panel is created for a distinctive geometric perforation pattern mirroring building resident mathematicians and scientists' research focus. The patterns range in line and diverge. Some geometric patterns with circles, hexagons, triangles, and squares are seen flourishing into an opaque mesh, and thereby lead to a higher level of control over the received sunlight.

Figure 1. An example of shading devices used as an essential part of a structure for controlling solar radiation is the dynamic windows at the Simon Centre for Geometry and Physics at the State University of New York, USA (2010) (Source: https://www.hoberman.com/portfolio/dynamic-windows/).

South Korea's Thematic Pavilion is also an example of an integrated self-shaded device. It is inspired by a South African flower and has a movable 90-degree flap. The main use of the principle is solar shading with minimized view obstruction when cloudy weather and full protection from the sun when sunny [31]. The Pavilion is based on Strelitzia Reginae's movements. The perch curves and the petals open whenever a bird lands on the flower, revealing the anther to the bird and making pollination possible. Researchers at the University of Freiburg's Plant Biomechanics Group used this concept for shading. They later designed a shading principle wherein shading is available when needed and can be moved away when not, preventing view obstruction. The Pavilion's shading method minimizes the sun's radiative heat using 108 kinetic lamellas. The glass-fiber-reinforced polymers are used to make the lamellas for low bending stiffness and high tensile strength, allowing for reversible deformations. This principle was needed in adjusting the lamellas' bending to control solar input. The solar panels on the rooftop charge the actuators. Similar to an anther moving in and out during pollination by the bird, the lamellas twist to control the solar gain.

2.2.8. Thermoregulation

A critical mechanism in cooling the building is efficient thermoregulation. One of the manifestations of inspiration from termite mounds in thermoregulation (for cooling purposes) is Western Australia's mounds caused by compass termites [32]. The compass termites form an almond-shaped plan with a long axis oriented towards the north and south. The heat from the morning sun is absorbed through flat sides, and the mid-day heat is least absorbed by minimizing the exposure area (Figure 2). Termite also controls ventilation tubes. The rising inside temperature increases, opens the ventilation tubes, and lets the heat rise through a stack effect.

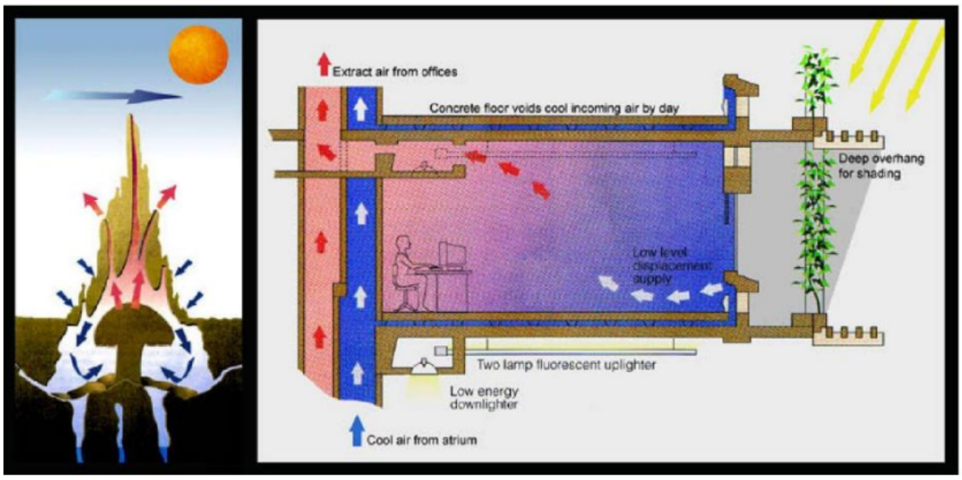

Figure 2. Section of a termite-inspired building that can cool itself (**Left**), Heat circulation in a room and a termite hill (**Right**) (Source: https://parametrichouse.com/biomimicry-architecture-2/).

The office buildings and shopping complexes in the Eastgate Centre have stable air temperature indoors all year. The center does not use mechanical cooling or heating system and consumes only 10% of the energy used in a conventional structure. Its porosity (Figure 3) causes the vents to pull in air, which cools as it enters the building because of heat-absorbing concrete slabs. The center's system is highly effective because the accumulated heat is sent to the slabs. Losing or gaining air depends on whether the concrete or air is cool. The air moves into the occupied spaces, then rises and flows up through exhaust. The released cycle draws through the Structure, consistently circulating fresh air.

Figure 3. The Eastgate Centre has mimicked termite performance in passive cooling through the use of local material and porous building.

The building's self-contained system is used for night ventilation. The high-volume fans move at a rate of 10 air changes/hour. The air goes into occupied spaces through centralized ducts. The air travels via hollow floors and is released from the low-level window grills [33].

The design concept integrates the regionalized stone style and the international glass and steel style. The building's cooling system is inspired by the local termite hills' passive cooling. The local biological system's design made the mimicry environmentally conducive and provides a network that sustains comfortable temperature even without a heating, ventilation, and air conditioning (HVAC) system. To ensure termite survival, the hill's internal temperature must be sustained at a constant temperature of 30.6 °C, but its external temperature may vary between 1 and 40 °C. Termites constantly adjust the air sucked through the mounts to ensure the survival of the fungus they consume. The vents are adjusted to open or close, depending on the required changes. The surrounding clay absorbs the heat and cools the air. The warm air in the mound rises through the central ventilator, releasing hot air to outdoor spaces and absorbing the cool air.

2.2.9. Lighting

Lighting has a well-established impact on human wellbeing and lifestyle. Tado Ando and Le Corbusier highlighted the fundamental role lighting plays in buildings and how it impacts us in three ways: radiation, our visual systems, and our circadian system [34].

Biomimicry offers diverse potential solutions and inspirations for designing lighting in architectural projects. Nature takes two aspects of light and color. Therefore, lighting must be considered when designing a biomimicry-inspired project.

One of the biomimetic design concepts which can be used in lighting design is gathering and focusing the light. For example, an anthurium offers some interesting aspects for collecting light in diffused conditions. Similarly, a spookfish inspires the idea of integrating a symmetrical pair of mirrors in the atrium spaces to reflect the light into building interior spaces [35].

For example, Pawlyn's recent project, The Biomimetic Office, is inspired by the spookfish's (Figures 4 and 5) [1] way of focusing low light levels. Architects can emulate the spookfish's ability when designing buildings. At first, this vertebrae spookfish was believed to have four eyes but was later found to utilize mirrors instead of lenses to focus light with eyes. Each eye has two connected parts. One points upwards and towards daylight, whereas the other points downwards. A mirror is used for focusing low-intensity light from bioluminescence. Pawlyn uses the spookfish's mirroring method to disperse natural light in his building, reduce energy use and raise occupants' wellbeing.

The angled plates of the mirror in the spookfish eye create a curved shape that allows the maximum amount of reflected light and the sharpest possible image (Figure 5a,b). The fish is predicted to change the mirror's position to center on objects from varied distances.

Minimizing the self-shading through the building is another concept widely used in lighting design. Another biomimetic design concept in lighting is minimizing the self-shading through the building itself. This principle is mainly seen among plants with phyllo-tactic geometry is often employed in the lighting design of buildings. Their form deeply harnesses the light. These projects used the Fibonacci rule on the ratio of series of repeating spirals.

In [1], the architect also proposed phyllotactic towers that act as a private garden for each housing and maximize solar heat gain and energy harvesting opportunities. Saleh Masoumi, the architect of Verk Studio in Iran, offered a novel solution to residential towers. His designs are inspired by the structure of living plants, providing each residential/work unit with 'yards'. In botany, phyllotaxis or basic leaf patterns could be alternating or opposite around the plant's stem.

Figure 4. Exploration Architecture's Biomimetic Office mimics the spookfish's eye structure (https://www.dezeen.com/2020/10/22/michael-pawlyn-exploration-architecture-dassault-systemes-video/, accessed on 22 October 2010).

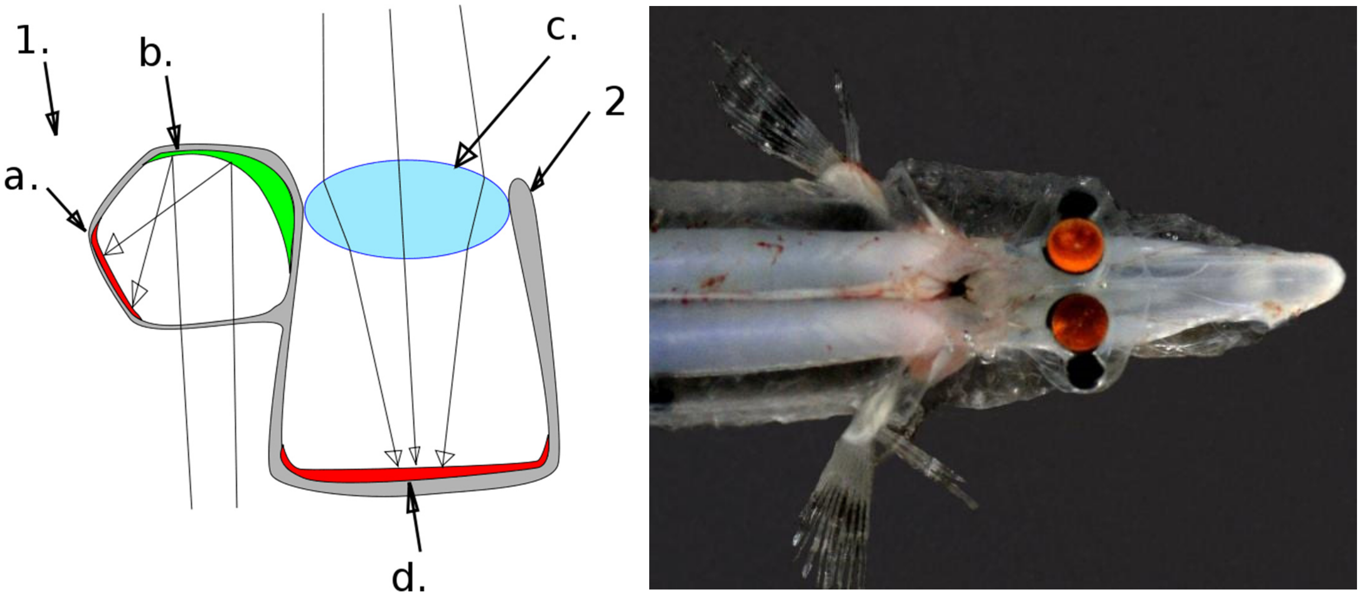

Figure 5. The downward-facing eye of the brownsnout spookfish (1) centers light on the retina (**a**) using reflective crystals (**b**). The main eye (2) uses a lens (**c**) and center light on the retina (**d**) (Left). The brownsnout spookfish's additional eye structures let the fish see below. (Credit: Florida Atlantic University (Right, (Source: https://asknature.org/strategy/extra-eyes-direct-light/).

3. Biomimicry in Structural Engineering

The age of industrial evolution devised the divergence of humanity from nature [36]. However, engineers almost always constructed structures and machinery using the 'heat, beat and treat' principle [2] by applying large amounts of heat, large pressure, and various toxic chemical treatments. A rapid increase in greenhouse emissions and carbon dioxide in urban areas has led to serious environmental degradation and posed great risks for public health. The construction boom and built environment are known as major contributors in accelerating these degradations and generating a high level of pollution and energy demand [37]. Furthermore, products developed by humans often cannot be recycled, thus polluting the planet utilizing land waste.

Although biomimicry has attracted reasonable attention in the fields of mechanical engineering (robotics), materials science (intelligent materials), and biomedical engineering (prosthetics), it remains a grey area in structural engineering. Engineers and environmental scientists have attempted to mimic forms and designs of nature to apply findings to practical structural engineering problems and achieve reasonable solutions (higher strength or fewer resources required) that address environmental and sustainability issues. Imitating shapes and geometry of structures from nature is the best-known biomimicry in structural engineering. For example, the roof of Pantheon in Rome gains its strength from its multi-dimensional curvature by mimicking the shape of a seashell, resulting in lightweight and reduced reinforcement [38].

By studying how natural structures/systems sustain loads and optimize resources existing structural design strategies can be improved or reinvented to achieve efficient and sustainable built environments. Sustainable interferences are needed while creating these built environments and not after building them [37].

In addition to studying the forms and designs of nature, imitating the natural processes is another promising avenue for adopting biomimicry to construct contemporary built environments. Superstructures, such as dams, have been built to generate power for human activities, divert and supply water for agriculture, prevent flooding and stabilize the water. Although hydropower is considered green energy, greenhouse gases have been generated by constructing dams. Beavers create dams by piling up twigs, branches, and trunks of trees (Figure 6). The construction process of beavers' dams reveals the acquisition and utilization of local materials, the choice of reusable and recycled materials, and the increased efficiency of the system.

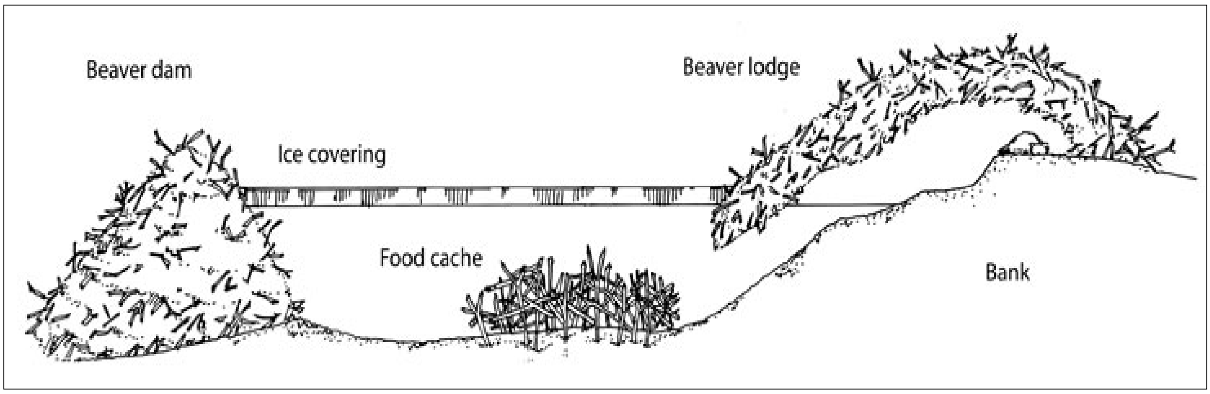

Figure 6. Diagram of beaver's dam and lodge (Source: https://www.hww.ca/en/wildlife/mammals/beaver.html).

The current construction process is typically powered by renewable energy, such as chemical energy or sunlight. As a result, if scientists and engineers can crack the secret of 'natural construction', our manufacturing and construction processes will face a breakthrough. The manufacturing process no longer requires enormous energy input, which can significantly reduce cost and pollution. Engineers and scientists have many future possibilities in mimicking nature and developing engineering designs and construction.

However, we must first unravel and understand the basic principles. A fundamental point of biomimetic is to understand the principles and the reasons why things work in nature. According to Biomimicry 3.8 (2021), the six major biomimicry principles are as follows:

(i) Resource (material and energy) efficiency
(ii) Evolution for survival
(iii) Adapting to changing conditions
(iv) Integrating development with growth
(v) Being locally attuned and responsive
(vi) Using life-friendly chemistry

Given that structural engineers' knowledge of biology is limited, there is a need to raise awareness of these principles and their use in structural engineering.

3.1. Concept of Biomimetics and Structural Engineering Design Process

Biomimetics benefits the structural engineering design process. In structural engineering, the main objective is to design structures to achieve functionality and maintain their structural integrity during the design life. For example, structural engineers design various buildings, ranging from small domestic houses to large commercial skyscrapers. Each building has its specific purpose (residential, commercial, or recreational use) and constraints (height limitation reinforced by local government authorities). Thus, the design of each structure can be treated as a unique engineering problem. In nature, structures can be nearly any living organism or products made by them, for example, pine trees or honeybee combs. By studying how these natural structures sustain loads and optimize with resources, structural engineers attempt to innovate existing structural design strategies to achieve efficient and sustainable structures.

For engineers studying biomimicry, three major areas are worth investigating. For example, in organisms, organs and organisms (structures) are made up of different kinds of tissues, which are also made up of cells; a cell is the simplest unit [2]. Structural engineers and builders have used an analogous hierarchy (cell-material, tissue-shape, and organism-structure).

3.1.1. Materials

Materials are the smallest, indistinguishable building blocks in the structure. Natural materials have always been in use. The first tools our ancestors used were little more than sticks or stones picked up and used to hammer open food. In the modern era of engineering, where specific properties are needed for calculations or factors of safety, natural materials have become less popular in structural uses and not obsolete.

Biological materials are elegant and practical in the engineering field. They provide sufficient strength and other special characteristics while remaining relatively light in weight. Most of the natural materials are biodegradable, which increases their value in an era of sustainability. Biomaterials have two main classes: elastic-tensile biomaterials and hard rigid biomaterials. Tensile materials are mainly composed of protein, whereas rigid materials are formed by combining the protein with minerals (primarily calcium or silica) [39].

For example, natural silks have been found to have excellent strength and extensibility [40–42]. Spider silks have low density, tensile strength exceeding 1000 MPa, and extensibility of approximately 0.27, which is way beyond the yield strain of steel (0.0025). In short, natural protein silks are one of the best structural bio-materials made by nature. They have incredible tensile capacity and impressive extensibility, not to mention their low density compared with traditional steel wire. If scientists and engineers can find a way to mass-produce natural silk with a big diameter, the size of concrete reinforcement or cables can be substantially reduced.

Another particular type of protein worth discussing is resilin and abductin, which do not have extremely high tensile strength or elasticity. However, the two types have a special ability to store energy and release it back with high efficiency.

Abalone shell is another great example of nature's wisdom in building construction by using the nearby environment to minimize energy use. Besides its amazing growth mechanism, the abalone has outstanding mechanical properties, as its average fracture strength is 185 MPa [43].

Another type of biomaterials that are also mineralized is bones. Bones are the essential component of our body, performing mechanical, chemical, and biological functions. They are a highly hierarchical structure and have incredible mechanical properties. Bones have two types: cortical (or compact) and cancellous (or trabecular). Bones have a highly hierarchical order. The main components of bones are bone crystals, collagen, and water. The mechanical properties mainly depend on individual bone porosity, degree of mineralization, and bone age [44]. As a result, similar to most biomaterials, their mechanical properties are varied.

Enamel and dentine, (which are known as the stiffest biomaterial in the human body) are mainly found in human teeth, form the other type of bio-materials. Enamel is the stiffest biomaterial in the human body. It has a yield stress of 330 MPa and a Young modulus of 83GPa [45]. Therefore, the yield stress of enamel is comparable to steel. Furthermore, compared with other metals, such as steel, enamel displays metallic-like behavior in a stress-strain relationship and crack initiation even though most enamel is made up of brittle hydroxyapatite crystallites [46]. This finding shows nature's ability to achieve metallic mechanical properties from brittle ingredients using hierarchical order or special arrangement.

These examples show that using natural materials does not necessarily mean a compromise in performance and can indeed be of significant benefit. Thus, why are raw materials not used more today? One major problem of applying the discovery directly to the structural engineering field is that most bio-materials found in nature cannot be mass-produced, and their durability is relatively low. Thus, the problem of mass-producing biomaterials with excellent mechanical properties and increasing their durability will be the most important future research direction for engineers and biomimetics.

The majority of biomimetic materials have been created in Europe, and the form or mechanism of insect or plant organs have been the source of inspiration. Given the rapid advancements in the area of nanotechnology, the biomimetic wave has been also extended to mimicking animals. Japan and the USA are active research participants, and Europe is at the center of growth. The biomimetics research front is proceeded by nanotechnology and dynamically developed using electron microscopes similar to scanning electron microscopy, which allow us to study the physical properties, structure, and function of natural organisms. Given these nanotechnology tools, biomimetic engineers could evaluate using the single-cell scale, especially for organelles of cells and cell interactions. The biomimetic analysis of cell organelles' communities and their structures would provide insights into the development of nanoscale constructs that may act or function during cellular construct performance.

3.1.2. Shape

The shape is the macro arrangement of materials that serve a function. Nature often uses geometrical properties and specific allocation of materials in a macro sense to improve efficiency to resist a combination of loads. For example, plants and animals are constantly under the effect of various loads. The load cases nature often faces are similar to buildings developed by humans. Trees, one of the most stable living structures on the earth, display many structural similarities to load-bearing structures, such as residential buildings. In the case of horizontal branches of trees, the gravity load causes bending stresses along the branches. As the bending axis is relatively stable, horizontal branches develop an elliptical section. The main tree trunk is subjected to wind load as a major lateral load, and its direction is unpredictable. Thus, tree trunks develop circular sections to ensure loading in any direction. The simple mechanics of solids calculations confirm that hollow circular cross-sections are optimal for members subjected to axial, bending, and torsional combined stresses. However, if the direction of loading is known, the hollow elliptical section has an even higher capacity to resist combined stresses, as typically adopted and applied in nature.

Furthermore, to prevent buckling, bamboos develop a hollow section with some nodal septum. Having a nodal septum in equal spacing enhances the buckling resistance of bamboos greatly. It also prevents ovalization from occurring inside the cross-section and stops longitudinal cracks from extending [47].

Besides adopting hollow sections, natural structures often develop tapered members. Cracking is another challenge faced by many organisms. Although no conclusion is drawn about the reason for crack initiation, most scholars have suggested that cracking may result from minor defects or localized damages of structures. In reality, virtually any large structures have cracks. However, cracks allowed to grow or propagate can lead to fracture or reduction in structural capacity. As a result, nature develops several methods to stop crack propagation, such as using composite (laminated) structural materials and placing voids at appropriate places.

Nature has developed excellent strategies to allocate the material to maximize its capacity to resist various mixed actions. Thus, studying how nature combines and arranges biological materials together will provide an understanding of the optimal shape with the optimal proportions of ingredients needed.

3.1.3. Structure

Structural engineers can learn much from nature because it is a self-optimizing system. Nature inspires structural engineers in the process of designing and building a structure that has a high level of adaptability and requires a minimum amount of maintenance. Thus, future structural systems can be considered intelligent, but these basic principles must be first unraveled and understood. Biologists and engineers agree that a systematic analysis in biomimetics is yet to be developed [38].

The structure is the arrangement of different shapes (or members) to solve a given engineering problem. For example, the supporting system of our human body mainly consists of hundreds of bones, ligaments, and tendons. The interrelationship of the bone members has modern applications. The human thigh bone has a high load capacity, which can withstand one ton when in a vertical position. The femur head extends sideways into the hip socket and bears the body's weight off-center. The thigh bone consists of tiny ridges of bone known as trabeculae which are in fact series of studs and braces that are positioned along the force line when standing. The bone structure inspired engineers to decrease the impact of load on the building. In fact, nature strengthens the bone at a level that is required [48].

In 1866, the Swiss engineer Karl Cullman translated these findings into applicable theory. In 1889, French structural engineer Gustave Eiffel was inspired by the concept of "building along the force lines" to design the Eiffel tower. The curve in the Eiffel tower iron is similar to the curve in the femurs' head. The bending and shearing effects caused by the wind would be transformed into compression [48]. From the Eiffel Tower base (Figure 7), the lattice structure of the studs and braces can be seen. The same approach was utilized to design the World Trade Centre.

Bone and joint mechanisms in humans or other animals are one of the most wonderful and simple ways of achieving mobility. It can dislocate the joint under excessive movement or sudden impact without fatal failure in the bone. Furthermore, joints can be relocated again after treatment. Thus, nature has developed a mechanism for repairing and healing itself while adopting simple methods. Suppose this idea can be applied to the field of structural engineering. Thus, engineers may design buildings that can mimic the joint system in humans such that, under the sudden impact (i.e., an earthquake), the building can absorb the energy by dislocating some of its parts and then reconstructing by simply relocating structural connections (joints) back together, which could result in safer buildings and the reduction in construction costs.

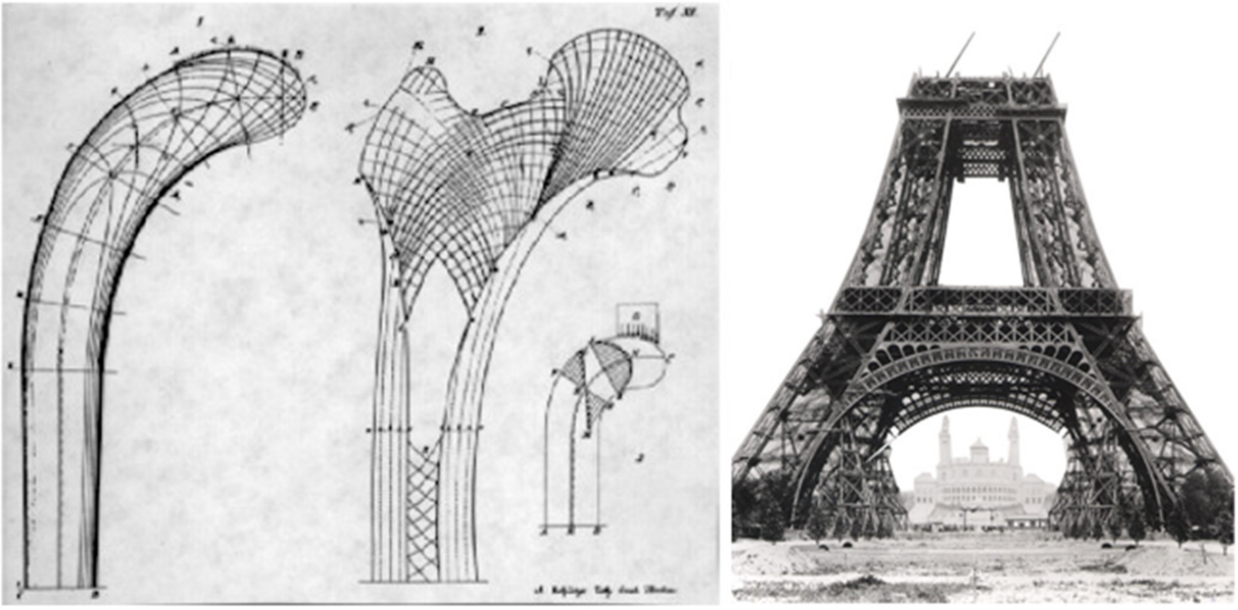

Figure 7. Crane principal stress lines and trabeculae lines on the femur (**left**) [49]; the base of the Eiffel Tower (**right**) (Source: Flickr.com).

Spider webs have some geometric features. Spiders manufacture their webs with two distinctive treads to prevent prey break or bounce back from the web: a strong stiff tread for supporting or structural purposes and the flexible and sticky tread to retain the prey on the web [50].

The tree rooting system is a perfect example of inspiration from nature to withstand loading [36] Compressive buttressing, tensile buttressing, and tap rooting are three mechanisms adopted by various types of trees to resist overturning. Although the structural capacity of the amoeba cell is still under research, it is still a natural wonder that a single-celled organism, without any brain or nervous system, can build a simple yet elegant structure. The strategy of having a spherical shape may also demonstrate the wisdom of nature because a spherical shape is proven to have better resistance on impact from arbitrary directions. If the mechanisms of how amoeba constructs the shell are known, engineers and scientists may develop excellent construction processes, which minimize the need for precise calculation and computation power [28].

Honeycomb is another live structure that inspired many structural engineering projects [51]. A popular application is the utilization of the honeycomb cell for sandwich construction (Figure 8, which is a highly valued structural engineering innovation. The sandwich components are rigidly joined with the core-to-skin adhesive to act as one unit with high rigidity in torsion and bending [52]. Besides saving building material, such a sandwich structure also offers other benefits (i.e., durability, low weight, high stiffness, and stability) compared with usual materials (Figure 8). Thus, materials are used efficiently without sacrificing strength. For instance, bees connect and direct one another through a 'waggle dance' and set up vibrations. Honeycomb is a small dimension structure, and such tremors can be likened to earthquakes. The walls of the honeycomb can absorb these potentially damaging vibrations. This great structure can be imitated when earthquake-proof structures are designed. Jurgen Tautz of the University of Wurzburg in Germany explained that honeybee nest vibrations are similar to low tremors that bees generate. Thus, seeing how the building responds is interesting. Structural engineers can predict building parts that are in danger of earthquakes by considering phase reversal. Consequently, they can strengthen these parts or introduce them into areas that are not critical to absorb damaging vibration [53].

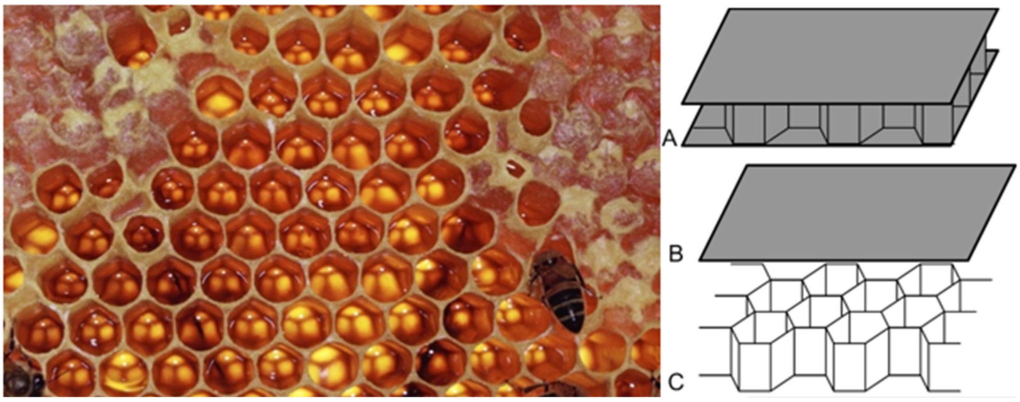

Figure 8. Honeycomb (**left**) and the sandwich structure's schematic view (**right**) (Source: https://en.wikipedia.org/wiki/Sandwich-structured_composite).

4. Biomimicry and Energy Retrofication

Several biomimetic technologies aim to learn from the living world to substitute renewable sources' current fuel energy systems, such as solar and wind energies. Providing energy for buildings and cities is one of the major concerns of today's society mainly because of the urgent need to tackle issues raised by climate change and non-strategic urban planning decisions employed in cities within the last couple of decades.

Biomimetic has also inspired engineers and designers in the development of non-conventional energy resources, such as learning from plant's photosynthesis process to generate solar cell system [54,55], mimicking the butterfly wings in solar panel technology [56], mimicking the ferns in creating more efficient electrodes for solar storage systems [57], mimicking the frog nerve rays in producing batteries, mimicking the foam nests of the Tungara frog and red panda digestive enzymes in the production of biofuels [58], mimicking the movement of fish in creating more efficient wind turbine technologies [59] and mimicking the movement of certain fish in the development of ocean driven energy technologies [60].

Several examples of living ecosystems are highly energy-efficient and are often used as the best inspiration for what humans can do to not depend on fossil fuels. Biomimicry offers great potentials for learning from nature and coming up with solutions that lead to a lower level of energy consumption. Four principles are used in biomimicry to reduce the overall energy consumption; 1—decreasing the demand, 2—identifying unlimited sources of energies; 3—sustainable energy distributing systems, and 4—decreasing the non-toxic flows compatible with w wide range of systems.

Encycle's SwarmLogic utilizes an exceptional algorithm that lets electric appliances interconnect with one another and save power. Almost all major structures have HVAC systems. However, HVAC systems can be the biggest energy consumer and have the highest cost of building maintenance. Various building equipment is operated in isolation from other equipment, following a single timer or thermostat in the facility. Given that these loads do not communicate with one another, they usually operate simultaneously, needlessly increasing energy usage and rising costs. Bee communication in colonies is an inspiration for a building energy management system. Honeybees interconnect and manage individual behaviors to shape a collective organization that effectively feeds colonies and builds hives.

The project developed Swarm Logic to lessen the demand for peak energy utilization by up to 30%. The energy-efficient technology integrates a structure's controls to instantly and dramatically reduce power costs. Controllers of Swarm Logic establishes a wireless mesh network of electric-consuming appliances and enables intercommunication autonomously. The interconnected appliances spread out power demand through a custom algorithm that is inspired by honeybee communication. The outcome is referred to as peak demand shaving.

One of the most well-known examples of biomimicry in reducing energy consumption in buildings is the CH2 building in Melbourne, a six green star building, which was built at a cost premium of 22.1%. However, given that productivity increases of 10.9% from staff attributed to the new building, payback was between 5 and 7 years [61,62]. In this building, the air is conditioned through the use of cleaned water in the sewage system. This process has been inspired by certain termite species that employ aquifer water as an evaporative cooling mechanism. Termite digs a deep tunnel to reach the water and therefore, its cooling impact is a remedy to reduce the extreme heat and keep the mound within a one-degree temperature variation range.

The concept of Biomimicry has also inspired the use of renewable energy systems in the built environment and technologies and led to significant savings in energy usage. For example, the tubercles on the flippers of humpback whales have been the main inspiration for a type of wind turbine in the project of reference [63]. Most wind turbines stop working under low wind scenarios. However, this project's wind turbine blade has been designed so that the performance is not adversely affected even under slower speeds. This project achieved a 20% improvement in the annual output due to employing biomimicry-inspired principles in design and construction.

The concept of "Green Power Island" is based on the necessity to provide diverse forms of energy storage to accommodate a different range of renewable energy outputs and generate resilient systems. The proposal provides a solution to this challenge by creating a large reservoir with 22,000,000 m^3 capacity and a generation capacity of 2.3 GWh. The reservoir generates power by letting the sea flood back in via turbines that are located in the flatlands around the reservoir and provide the best access to the wind. The site next to the turbines is also used as a platform to grow biomass and food crops and thereby deliver multiple benefits. The reservoir is also equipped with series of photovoltaics that enables the possibility of solar tracking. Surrounding lands of the island provides the best platform to breed seabirds. Below the sea level, the sloping border walls have created a rocky shoreline. There is a lack of biodiversity in flat rocky seabeds, and the rocky shorelines are in contrast known as rich habitats. Therefore, this proposal can effectively enhance biodiversity [1].

5. Summary and Conclusions

This study presented biomimicry's potential to provide sustainable solutions to human challenges, especially designing and constructing structures. Biomimicry is also helpful in the creation of novel materials, technologies, and products with viable attributes. However, biomimicry knowledge is lacking among stakeholders in architecture and structural engineering. Thus, biomimicry's adoption and application are hindered from enhancing sustainability in the construction and design industries. Principles of biomimicry also play an essential role in evaluating sustainability because they are common tools and vital checklists that are strictly used when focusing on sustainability. Professional awareness, education, and training on biomimicry of stakeholders and professionals should be stimulated to ensure its wide adoption and practice.

This review showed that biomimicry's connectivity has been supported throughout history. After the Renaissance, humans developed a better understanding of physics and mathematics. They were able to form large metal products with fuel-powered machinery with the aid of the industrial revolution [38]. As a result, structural engineers and designers have preferred working with forms, shapes, and materials with uniform properties throughout and members with easily determined mechanical properties. Principles in nature's prototypes were often excessively complex to be transferred for engineering and design purposes; built environment professionals often have members with homogenous non-composite materials, shapes and forms with rigid rectangular shapes as opposed to using composite, flexible, and force adaptive members, commonly found in nature [64].

Nature builds things more gently. Biomimetics has discovered that nature recycles everything used, uses sunlight as the primary energy resource, and fits its function [2].

Biomimicry also aims to provide innovative, sustainable solutions to engineering problems by studying biological modes and systems found in nature. Therefore, biomimicry has a great potential to benefit structural engineering and the design process.

Architects and structural engineers require great awareness to achieve efficiency and sustainability in buildings, especially in this era when meeting the sustainability targets is more critical than in the past. The natural world provides an extensive design database that can inspire creative thoughts. Most efficient buildings adapt to their surrounding environment and use the environment to benefit them. Consequently, the value of the lessons from nature should be recognized, and these innovations should be adopted in developing structures that fit with their surroundings.

It is also worthwhile mentioning that the majority of functional mimicries were derived from insects and plants' micro-and nanoscale parts. Recently, given the nanotechnology advancement, a new wave of biomimetics has been extended to animal imitation. Europe has been the center of development, especially of most biomimetic materials. Japan and the USA actively participate in research. Biomimetic research front is vigorously advanced by nanotechnology and electron microscopes similar to scanning electron microscopy, enabling the observation and analysis of natural organisms' physical properties, structure, and function. These tools of nanotechnology allow biomimetic engineers to study at the single-cell scale for cell organelles and interactions. The analysis of cell organelle communities and their structures offers us insights into developing nanoscale constructs during the performance of cellular constructs.

The design and management of future cities could also incorporate biomimicry but may have big obstructions. Adopting transdisciplinary solutions needs considerable changes to city powers and the cooperation among stakeholders, systems, and utility providers. Furthermore, the public, local authorities, developers, and designers must have adaptive mindsets to exploit biomimicry's potential fully.

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