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Bio-inspired design trends for sustainable energy structures

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Bio-inspired design trends for sustainable energy structures

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Abstract. Researchers and engineers are constantly looking to nature for design inspiration as they work to create novel and effective energy conversion structures. Engineers are developing durable and resilient materials to survive extreme weather conditions and environmental issues using inspiration from the Nenuphar's durability in adverse aquatic environments and the Sunflower's adaptation to vary climatic situations. The analysis of new design ideas in renewable energy systems in this research was inspired by the Nenuphar (Water Lily) and the Sunflower. The Nenuphar's exceptional capacity to float and large leaf surface make it a model for enhanced water-based energy conversion systems. Researchers have been looking into novel concepts like floating solar farms and wave energy collecting platforms after being inspired by the Nenuphar's buoyancy and ability to efficiently use sunlight. Solar panel integration with water features can boost overall energy output while preserving precious land resources. The Sunflower, known for its phototropism and effective sun-tracking mechanism, offers suggestions for improving solar energy harvesting. Advanced heliotropic solar panels have demonstrated promising results in boosting energy production throughout the day by mimicking the Sunflower's ability to follow the trajectory of the Sun. These designs maximize energy outputs and boost overall system efficiency by maximizing solar exposure. Embracing these bio-inspired concepts can lead to the development of sustainable and efficient energy solutions, contributing to a greener and more sustainable future. Furthermore, the integration of smart technology and artificial intelligence is on the rise to optimize energy conversion structures.

Keywords: Bio-inspired, Energy conversion, Nenuphar, Sunflower, Sustainable solution

1. Introduction

Nature-inspired energy conversion design systems aim to provide sustainable solutions that minimize environmental impact [1] while optimizing energy production and utilization [2], [3]. These approaches can help address the challenges of climate change and promote a greener and more sustainable energy future [2]. Many researchers and engineers are actively exploring these concepts to create a positive impact on the planet [4].

Natural systems are self-optimizing, consequently structural engineers can learn a lot from them. Structural engineers are inspired by nature when designing and constructing a structure with a high degree of adaptability and little need for maintenance [5]. The global push towards renewable energy sources has led to innovative designs in energy conversion structures [6]. A 2MW integrated floating-wind turbine system was deployed as part of the Floatgen European research project on offshore wind energy [7]. It has been operating successfully since then, and it has paved the way for the development of other floating wind farms [7,8].

Many structural engineers have been driven and inspired to look outside of the box for creative problem-solving approaches by bio-inspired design [9]. Bio-inspired designer concur that biomimetics has not yet undergone a thorough investigation [4, 10]. Numerous engineering applications require the availability of lightweight structures with great energy absorption capability, as is well known [1, 4, 11]. Bio-inspired structures have been demonstrated to offer a considerable improvement in energy absorption capacity over conventional structures. These structures are inspired by various biological structures seen in nature. As a result, engineering fields have been using the biomimetic approach more frequently in recent years to design innovative, lightweight structures with outstanding energy absorption capability [1, 9]. Bio-inspired energy conversion structure design trends promise to revolutionize renewable energy technology and play a crucial role in combating climate change , the contribution of Bio-inspired design method is potential [12]. This review paper aims to provide a comprehensive design and production trends driven by nenuphar and sunflower structural features.

2. State of bio-inspired energy conversion structural design

Nature has served as a perpetual muse for architects and engineers, offering timeless lessons in efficient design and resource optimization. Sunflowers and water lilies, two iconic natural wonders, have inspired innovative structural design solutions that combine beauty with functionality. Bio inspired engineering design is the process of developing innovative and sustainable solutions for a range of problems, including energy technology, by taking cues from natural processes, patterns, and systems [13].

2.1 Biomimicry in structural design for renewable energy

Biomimetic design provides practical benefits and frequently leads to more durable as well as more ecologically friendly solutions by modeling performance and adaptability upon the principles of nature. In line with various energy conversion techniques, some of the prospective designs for renewable energy structures that were inspired by nature were thus outlined hereunder.

Bio-inspired Wind Turbine Design: Drawing inspiration from the aerodynamics of bird wings and the shape of tree leaves, wind turbine designs could mimic natural forms to improve efficiency and reduce noise [2,3, 9]. Studying the way birds and trees adapt to wind conditions can lead to more streamlined and silent turbine designs. In several industries, including renewable energy, biomimicry—the practise of using cues from nature to address human problems—has emerged as a powerful technique. In the design of wind turbines, biomimicry shows a lot of potential [4].

Researchers may create wind turbines that are more sustainable, effective, and environmentally friendly by researching and modelling the efficiency and flexibility of natural systems. Scholars are undertaking to examine how biomimicry might revolutionize wind turbine design, resulting in cleaner and more efficient energy-saving solutions. Birds have evolved to efficiently navigate through the air, minimizing energy consumption during flight. Wind turbine blades can take inspiration from the shape and structure of birds' wings to enhance aerodynamics. Many birds can fly over great distances because of the highly effective lift that their wings provide. The cambered form and swept-back leading edge of bird wings, as well as other aerodynamic characteristics, can be used to construct wind turbine blades [6]. This may help to increase the blades' effectiveness and cut down on energy use. The shape of a bird wing and a wind turbine blade are comparable, as seen in Figure 1. The shape of the bird wing is an airfoil with a cambered surface, which indicates that the top surface is more curved than the bottom surface. The force that keeps the bird flying is lift, which is helped by its form. The form of the wind turbine blade is also cambered.

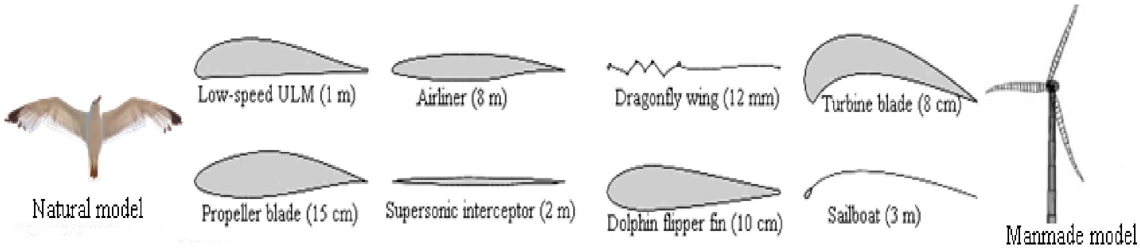

Figure 1. Bio-inspired wind turbine blade cross-section

By mimicking the flexible and adaptive wing movements, turbine blades can automatically adjust their angles and shapes to optimize energy capture under varying wind conditions. This biomimetic approach would lead to improved efficiency and stability of wind turbines, maximizing energy output. The need for the development of clean and renewable energy sources by world communities has never been more important. The use of palm tree leaves to design more durable wind turbine blades is one of the opportunities to develop adaptable engineering structures seen in Figure 2. Practitioners were inspired to develop flexible wind blades due to the fact that palm tree leaves have showed abilities to withstand strong winds and heavy rain without breaking.

Figure 2. Palm tree inspired flexible wind turbine blades.

Imitating the structures and textures of leaves, wind turbine designers can also reduce noise pollution caused by the blades. This biomimetic approach not only improves the overall aesthetic appeal of wind farms but also enhances public acceptance by mitigating the potential impact on nearby communities for generation of sustainable energy. Since palm tree leaves are made of a lightweight strong material and the foundation also anchored with many roots which can be an evidence for the state of wind turbine engineering design practices.

Engineers/Scientist has adapted solar panels to the efficient leaf structure and photosynthesis-enabling light-harvesting capabilities of leaves. Photovoltaic panels are analogous to green plant leaves in nature. To split water and produce chemical energy carriers, they absorb solar light and turn its energy into electricity (electrochemical energy). The chemical structure and function of biomolecules can be badly harmed by excessively heating leaves to temperatures above 40 to 45 ^{0}C. As a result, nature has created a number of adaptations that aid leaves in regulating temperature [14]. The first bionic photovoltaic panel was designed after typical tree leaf and twig structures observed in warm-climate regions and modelled as shown in Figure 3(a) and (b).

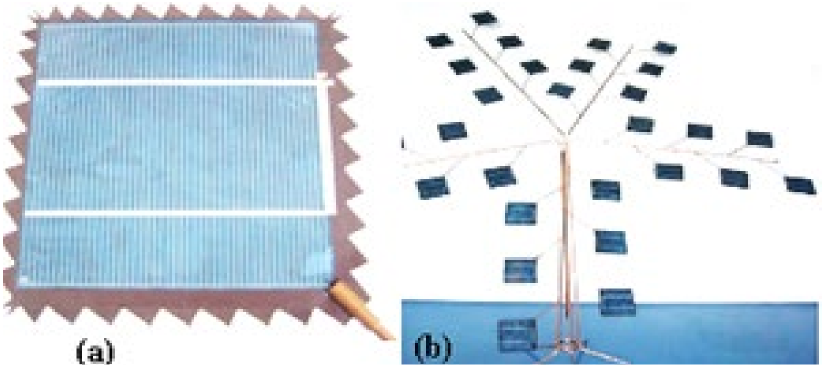

Figure 3. First model of a bionic photovoltaic leaf (a) and tree (b)

To increase light absorption and energy conversion efficiency, many researchers [2, 4, 11-12] have already begun to create solar panels that resemble leaf shapes. The mechanical and structural characteristics of the palm tree leaf-inspired solar PV structure depicted in Figure 4 that were investigated by [14], the designed prototype were tested with respect to mechanical and thermal properties, the design have provide a very acceptable outcome. Beside this the designed model was a lightweight moveable photovoltaic panel, which can be simply detached and re-assembled for installation at required place.

Figure 4. Palm leaf inspired photovoltaic structures.

There is an increasing interest in exploring alternative energy sources because of concerns about climate change and the need to reduce the dependency on fossil fuels. Accordingly, there is a greater need for clean energy sources that can convert energy effectively with the use of cutting-edge technological structures.

2.2 Nenuphar (water lilies) inspired renewable energy use structural design

Nenuphar is at the forefront of a cutting-edge technology model for renewable energy extraction, which includes wave solar and wind energy structures design and layout deigning. The actual model of nenuphar, if used for renewable energy conversion structure, will contribute to an effective use of land and geometries, especially for the wave energy source, which could significantly contribute to the world's electricity needs while reducing greenhouse gas emissions and optimising use of ocean surface area. So far, Nenuphar's model of a floating structure has created an innovative way of harnessing energy and turning it into electricity. Their design is based on the idea of "Nenuphar Islands," which are essentially collections of connected floating structures that were inspired by nenuphar pads. As shown in Figure 5 many lessons can be generated from the nenuphar front and back side orientations.

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Figure 5. Nenuphar natural model for Bio-inspired design

Furthermore, being capable of imitating natural systems for structural design that adopt weather condition for the source of renewable energy conversion with optimal land usage might provide a more reliable and consistent energy supply. Due to the fact several practises are going to use the water's surface to develop renewable energy. Figures 6a and b depict a three-bladed floating horizontal axis wind turbine and Figure 6c a floating twin vertical axis wind blade that both create energy while floating over the water's surface as nenuphar did for photosynthesis process.

Figure 6. Floated wind turbine blades design and operation

Nenuphar's (water lilies) leaves provide an inspiration for innovative floating solar and wind turbines design have shown the possibilities to capture solar and wind energy while efficiently utilizing open space in the sea surfaces. This concept opens up new possibilities for energy conversion structures that can harness other renewable resources in offshore locations. Floating platforms could be adapted to accommodate solar panels, wave energy devices, or even hydro turbines, tapping into a diverse range of clean energy sources [15]. By exploiting the vast untapped potential of offshore regions, these floating energy platforms hold promise in significantly increasing renewable energy capacity. This idea may inspire the development of energy conversion systems with adaptive capabilities to adjust to shifting environmental conditions. Structures could, for instance, change their orientation to maximize energy capture or retract some parts during extreme weather. These adaptable structures would increase safety while simultaneously extending the life and increasing the effectiveness of renewable energy installations.

Water lilies, with their unique floating leaves, have long fascinated scientists and engineers due to their efficient use of sunlight and water surfaces. Natural water lilies have a distinctive natural system with a variety of engineering characteristics that can be imitated. Maintaining buoyancy is aided by the transpiration process, which involves water being absorbed by the roots and released through tiny holes called stomata on the surface of the leaf. The exchange of gases between the leaf and the surrounding water and air, such as carbon dioxide (CO_2) and oxygen (O_2), is facilitated by nenuphar evaporation system. There are renewable structures that mimic nenuphar platform, as seen in Figure 7, however many of those energy-conversion structures still require engineers and scientist to extract the actual natural working system of nenuphar for advanced product development. The large, flat leaves of nenuphar (water lilies) are able to float on water because of their high tensile strength and low density.

Figure 7. Bio-Inspired Mega project engineering practices

The choices of design for ocean wave, solar, and wind energy converter structures can be driven by nenuphar patterns and other natural phenomena. Apart from these merits, an additional hypothesized design factor for the nenuphar leaf's working mechanism includes the following areas:

1. Leaf Design for Optimal Sunlight Absorption: Water lilies have large, flat leaves that allow them to float on water while efficiently capturing sunlight for photosynthesis. Floating solar panels can be designed with similar large and flat surfaces to optimize sunlight absorption. This design would enable the panels to capture more solar energy throughout the day, increasing overall energy production.
2. Angle Adjustment Mechanism: Water lily leaves exhibit a unique angle adjustment mechanism that allows them to orient themselves to face the sun. Floating solar panels can incorporate a similar mechanism to adjust their tilt or orientation based on the sun's position. This feature ensures that the panels are always positioned optimally to receive maximum sunlight, further improving energy efficiency.
3. Natural Cooling System: Water lilies thrive on water bodies due to their natural cooling system. Their leaves remain partially submerged, enabling them to dissipate excess heat and maintain a cooler temperature. By integrating a similar cooling system into floating solar panel designs, the panels can operate at lower temperatures, which enhance their efficiency and prolong their lifespan.
4. Environmentally Friendly Material Choices: Water lilies are part of delicate aquatic ecosystems, making their ecological impact crucial to consider. Similarly, floating solar panels should be made from environmentally friendly materials that are non-toxic and have minimal ecological impact. Using sustainable materials for their construction ensures that they do not harm aquatic life or the surrounding environment.
5. Integrated Micro-habitats: Water lily leaves provide habitats for various microorganisms and small aquatic creatures. A biomimetic approach for floating solar panels could include integrating small, ecologically friendly habitats underneath the panels. These micro-habitats can foster biodiversity and contribute positively to the local ecosystem, supporting aquatic life and helping to maintain the ecological balance of the water body.
6. Floating Foundation and Stability: Water lilies are naturally designed to stay afloat on water surfaces without sinking. Similarly, floating solar panels can be engineered with efficient floating foundations and stability mechanisms. This design ensures that the panels remain securely in place, even during storms or varying water levels, preventing any potential damage to the panels or surrounding environment.

7. Biodegradable End-of-Life Management: Water lily leaves decompose naturally, returning nutrients to the water ecosystem. In the same spirit, floating solar panels should be designed with consideration for their end-of-life management. By incorporating biodegradable components or easily recyclable materials, the environmental impact of decommissioned panels can be minimized.

2.3 Sunflower inspired energy conversion structural design

Solar cells can harness the power of the sun to generate electricity. With the help of nature inspired design integration to efficient solar cell development, it is possible to produce energy without using coal or other fossil fuels. It has been observed that sunflower plants follow the sun as it moves from east to west. According to research, flower orientations increase vegetative biomass and warmth, attracting more pollinators. Researchers have been drawn to study sunflowers because of their fascinating natural design, which enables them to follow the sun all day. Sunflowers maximize their exposure to sunlight due to a mechanism called heliotropism, which also to increases the effectiveness of their photosynthetic process [16]–[18]. Since sunflowers are one of many plant species that exploit sunlight effectively to accelerate its growth [17] it can serve as an ideal method of bio-inspired design imitation.

The clean energy that would be generated from solar energy is an abundant available renewable resource. Nevertheless, because photovoltaic (PV) panels have low energy conversion efficiency, capturing this abundant energy source continues to be difficult for massive commercial use [19,20]. Energy conversion efficiencies for PV panels that are offered for sale range from 14% to 22% [19], [21,22]. Environmental variables like sun irradiation serve to aggravate this low efficiency even further. Depending on where a PV panel is located, different amounts of solar radiation impinge on its surface. PV panels really produce the most electricity when they are perpendicular to the direct solar radiation beam, where solar radiation is at its highest [21,22]. Figure 8 depicts the sunflower's process for tracking the sun using heliotropism model.

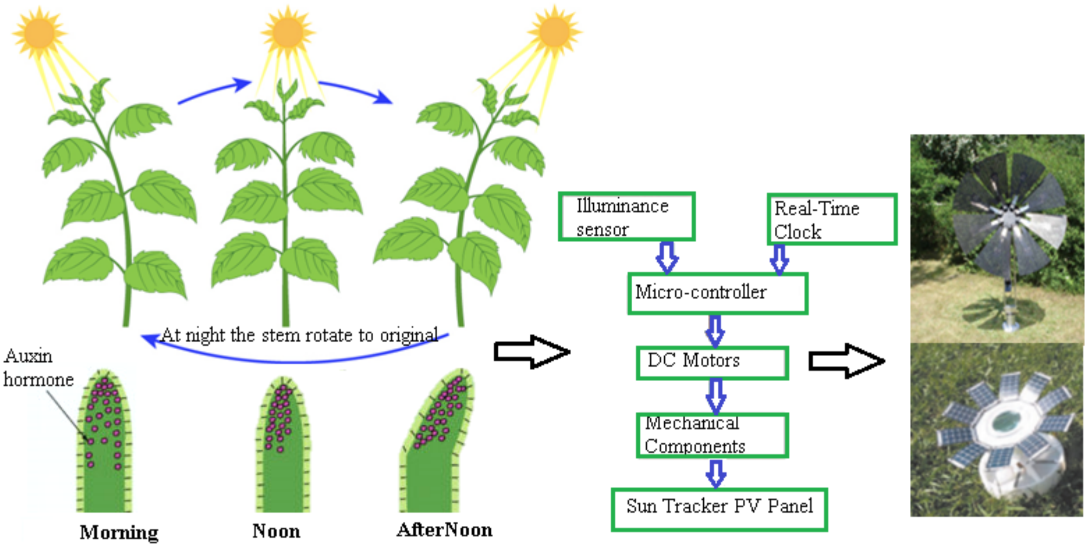

Figure 8. Sunflower inspired Solar PV panel design methods and operation

In an effort to imitate the sunflower natural manifestation, researchers have been created a manmade stem with unique components to support solar cells that can track sunlight, like sunflowers. These manmade stem-like materials can bend towards light, regulate themselves, and move into the proper position to collect solar radiation. Then, when the Sun moves, they make minor adjustments to stay put. As a result, they are able to collect 90% of the light that is available and is shining at a 75° angle on solar cells [23]. Beside this, sunflower energy systems include energy storage solutions inspired by the sunflower's capability to store energy through photosynthesis. Advanced batteries and energy storage systems mimic the plant's energy conversion and storage processes, efficiently storing excess energy for later use [23, 24]. Nature continues to be a source of inspiration for innovative solutions to contemporary problems. The sunflower-inspired energy conversion structural design is a prime example of how biomimicry can revolutionize the renewable energy sector. By emulating the sunflower's ability to track the sun and efficiently convert energy, Designers are moving closer to a sustainable future where clean energy is abundant and accessible to all. As we continue to develop and refine these systems, we can look forward to a brighter, greener future for our planet.

3. Opportunities and challenges of bio-inspired energy conversion structural design

The need for effective and efficient energy conversion technology is urgently developing because of the world's tremendous energy crisis. In their search for novel solutions, scientists and engineers are looking to nature for ideas. Biomimicry, commonly referred to as bio-inspired energy conversion structure design, has a lot of potential for overcoming these difficulties. To create more effective, long-lasting and flexible energy conversion devices, researchers are modelling natural processes. But there are difficulties and complexity involved with bio-inspired design projects. Some of the observed and reviewed opportunities and challenges in line with nature inspired design were discussed as follows.

3.1 Opportunities by Bio inspired design

Structures for energy conversion that are designed using bio-inspiration have a wide range of possibilities for innovation, sustainability, and effectiveness. Engineers and scientists can develop novel and effective energy conversion systems by modeling nature's solutions[16]–[19], [24]. Listed below are a couple significant prospects for structural engineering design using bio-inspired energy conversion.

3.1.1. Energy Efficiency: Energy efficiency is a growing concern for the built environment because of increased urbanization. The built environment has an impact on people's health and comfort in addition to emitting greenhouse gases that damage the climate. In the recent years, there has been an increase in interest in the use of bio-inspired methods in the built. In comparison to what the engineering-materials industry is currently capable of, nature has created structures with properties and mechanisms that are considerably superior. The extraordinary efficiency of biological materials, including their exceptional properties that depend on fragile constituents, their high performance per unit mass, and their numerous functionalities in addition to their mechanical abilities, has been primarily attributed to their hierarchical organization to be accounted as a lesson for today’s engineering design. Moreover bio-inspired designs offer the opportunity to significantly enhance energy conversion efficiency by learning from nature's time-tested solutions. This can lead to more sustainable and cost-effective energy technologies, helping to meet growing global energy demands while reducing greenhouse gas emissions [24-26].

3.1.2. Bio inspired design for unlimited source of Renewable Energy: Innovative thoughts have always been stimulated by nature to create new designs. Plants as well as animals offer a variety of structures having lower density, higher strength and high energy absorption that can inspire new design concepts with important characteristics [1, 6, 27, 29-31]. Bio-inspired structures have been demonstrated to offer a significant improvement over traditional counterparts for their applications in the energy sectors, by observing the critical functions of biological structures found in nature. The application of biomimicry principles to renewable energy technologies, such as solar panels and wind turbines, has the potential to revolutionize the energy sector sustainably with unlimited design options. Improved efficiency and adaptability can make these technologies more competitive and widely adopted for user demand [11, 27-29].

3.1.3. Nature as a Source of Inspiration for Innovation: Innovative thoughts have always been stimulated by nature to create new designs. Bio-inspired energy conversion structures can be integrated with biological systems. For example, artificial photosynthesis can be used to generate energy from sunlight, mimicking the efficiency of natural photosynthesis. This integration can revolutionize fields such as healthcare [32] and agriculture [25]. The study of natural systems serves as a wellspring of creative solutions to energy challenges [22]. By observing and learning from nature, researchers and engineers may unlock novel approaches and breakthroughs that lead to more sustainable and efficient energy conversion technologies Combining bio-inspired structures with existing technologies can create hybrid systems that leverage the strengths of both natural and engineered components. This synergy can lead to enhanced performance and versatility in various applications.

3.2 Bio inspired design challenges

To develop effective and sustainable energy conversion technologies, bio-inspired structural engineering design must overcome a number of constraints. These problems frequently involve several design, execution, and material considerations, making them complicated and multifarious. Following are some observed findings claimed as a challenge in designing renewable energy use structural engineering using bio-inspired methods.

3.2.1. Complexity and multidisciplinary: One of the primary challenges in bio-inspired energy conversion structure design is the intricate and multidisciplinary nature of the field. Nature's solutions have evolved over billions of years, resulting in complex, highly optimized systems. Likewise, the process of converting natural techniques into technological solutions for biomimetic designs may become a difficult interdisciplinary process [26, 31, 33]. By incorporating multiple kinds of mechanisms from many living things in search of superior solutions the design and implementation process complexity grows two three folds [29], [33-34]. Emulating natural systems requires expertise in biology, materials science, engineering, and other diverse disciplines. Bridging the gap between these fields can be a formidable task, demanding collaboration and communication between experts from different backgrounds [34].

3.2.2. Biocompatibility for engineering size design: Engineering design development must take biocompatibility into account, especially at the microscale where complex and delicate interactions with biological entities occur. Biocompatible engineering size design will be crucial in revolutionising healthcare and enhancing the lives of patients all around the world as technology keeps progressing. Even though nature provides a model for sustainable design in the actual translation of bio-system to engineering applications where bio-inspired structures interact as living organisms did, it will become impracticable in some areas like medical devices or biologically integrated systems that challenge to ensure prevalent biocompatibility. Systems of nature frequently function at scales that are substantially smaller than those of technical systems. Engineering systems that are compatible with biological systems may become challenging to develop as a result. Moving from small-scale laboratory prototypes to large-scale practical applications poses a substantial challenge. Scalability is crucial to make bio-inspired technologies economically viable and widely applicable. Maintaining efficiency, structural integrity, and cost-effectiveness when scaling up can be a formidable hurdle. To maintain effectiveness and functioning while maintaining the natural system for renewable engineering design is quite challenging [29, 33, 35-36].

3.2.3. Materials and manufacturing sustainability for bio inspired design model: The adoption of biomimetic approaches is constrained because conventional manufacturing processes that cannot accurately duplicate the complex biomaterials. Developing or finding materials that can replicate the properties of biological systems is a complex undertaking. Biomimicry often requires the creation of novel materials or the adaptation of existing ones. To maintain a similar design model to the imitated natural system, optimising manufacturing procedures for meeting the unique substances may prove challenging. In addition, the design and execution of bio-inspired energy conversion structures integrate sustainability of natural material manufacture into serious account. It is essential to ensure the sustainability for the manufacturing and disposal of bio-inspired renewable energy conversion structures to have as little impact on the environment as possible after their service life. Sustainability in materials and manufacturing is a key element of bio-inspired design, helping to produce more creative and eco-friendly solutions. This method addresses urgent environmental concerns while stimulating creativity and ingenuity by embracing the ideas of biomimicry, circular economy, and sustainable sourcing. Future developments in materials and manufacturing sustainability that will be advantageous to both people and the environment are on the horizon as we continue to explore the limitless potential of nature-inspired design [13, 15, 27-29].

However, bio-inspired designers and researchers have tried by providing unique solutions to a variety of technology and design challenges. In bio-inspired designs, there are a number of noticeable advantages that result from a smaller weight for the same amount of deflection, some of which can be explained as quantifiable values. Table 1 compares traditional and bio-inspired design parameters along with the advantages of using bio-inspired product design.

Table 1. Comparison of conventional and bio-inspired design parameters with BI product in use

Parameters	Conventional design (CD)	Bio-inspired design (BI)	Example
Weight reduction	Limited weight reduction achieved.	Significant weight loss while keeping the deflection the same.	A 20% reduction in wing weight over conventional designs was achieved by the Airbus A380's wing design, which was motivated by the structural concepts of bird bones [37].
Strength-to-weight ratio	Lower strength-to-weight ratio.	Higher strength-to-weight ratio.	The burr-inspired Velcro has a better strength-to-weight ratio than regular adhesives [38].
Material efficiency	Less efficient use of materials.	Improved material efficiency.	The lattice structure of the Tower of Paris, which was modelled by the natural plant stems, provided incredible durability while using less material [39].
Sustainability impact	Higher environmental impact.	Reduced environmental impact.	The kingfisher beak-inspired bullet train nose design lowered noise and energy consumption, making it more environmentally friendly [40].
Resilience	Less resilient.	Improved resilience to external forces.	Designs for biomimetic body armour modelled by fish scales inspiration for providing higher protection at reduced weight [41].
Adaptability	Less adaptable to changing conditions.	Enhanced adaptability to dynamic loads.	Improved energy capture and decreased structural fatigue are two benefits of wind turbine blades designed following humpback whale flippers mimic [42].
Cost savings	Higher production and operational costs.	Potential for cost savings.	The elephant-trunk-inspired Bionic Handling Aid boosts logistical efficiency and could lower costs [43].
Regulatory Compliance	May struggle to meet weight regulations.	Easier compliance with weight limits.	Bio-inspired design elements in the Boeing 787 DL, like lighter, more effective composite materials, aid in keeping to strict weight regulations [44].

Competitive Advantage	Potentially less competitive.	Competitive edge due to weight reduction.	Designing lighter, more aerodynamic cars using bio mimicry gives Formula 1 teams a significant advantage [45].

4. Research gaps

Numerous potential research gaps exist in the study of energy conversion structural design that takes inspiration from sunflowers and nenuphars (water lilies). These gaps can serve as a roadmap for future research and aid in the development of innovative, sustainable energy conversion systems. Potential research gaps are listed below.

1. *Productivity optimization details overlooked*: Explore methods to optimize the efficiency of energy conversion systems inspired by nenuphars and sunflowers. Investigate how design parameters, such as shape, size, and arrangement of nenuphars and sunflowers structural elements, impact energy capture and conversion efficiency which potential can be translated to machine learning.
2. *Material innovation for actual design lacks*: Develop and study new materials that mimic the mechanical properties and resilience of natural structures. Investigate the use of nenuphars and sunflowers materials for constructing mimicked energy conversion devices to enhance their performance and durability.
3. *Dynamic adaptation as natural system not implemented*: Research ways to create energy conversion systems that can dynamically adapt to changing environmental conditions, such as adjusting their orientation or configuration in response to varying sunlight, wind direction, or water flow.
4. *Efficient bio-inspired photovoltaic development challenged:* Explore the development of photovoltaic materials inspired by the light-absorbing properties of plant leaves and petals. Investigate their potential for improving the efficiency of solar panels, particularly in low-light conditions.
5. *Resilience to environmental stressors*: Investigate how natural structures like sunflowers withstand environmental stressors, such as wind, water, or pests. Apply this knowledge to design energy conversion systems that are more resilient and require less maintenance.
6. *Biological sensors and AI integration for bio-inspired design*: Explore the use of biological sensors or adaptations found in nenuphars and sunflowers to enhance the performance and safety of energy conversion systems. These research gaps highlight the diverse opportunities for advancing the field of energy conversion structural design inspired by nenuphars and sunflowers. Addressing these gaps can lead to the development of more efficient, sustainable, and environmentally friendly energy generation systems.

5. Conclusion

The application of bio-inspired design practises for the development and design of renewable energy structures is reviewed in this work in a systematic manner. Both the pros and cons of nature-inspired design have been examined, along with a possible list of subjects of study to be considered by those with appropriate expertise. The limited trail for sustainable energy conversation structure design was noted, but Nature gives a paradigm for intelligent, efficient designs that have been mostly disregarded or overlooked. The practise of mimicking nature is known as biomimicry, and it is something that humans have been doing for a very long time to find solutions to problems like hunger and shelter. The goal of biomimicry is to learn how nature lives and evolves so that it can be self-sustaining, not to imitate it in any way. The ability of nature to support life has required creativity. Through selection and testing throughout time, it has generated models, patterns, and solutions. Several of the challenges we now have are addressed in these solutions. Since 3-D printing employs materials that people are familiar with, including plastics, metals, and other materials, there may be an opportunity to use compatible elements to actualize the parts that were inspired by nature and manufactured for actual usage. On top of that, the incorporation of biological sensors and AI in bio-inspired design is now a promising innovation and technical frontier that has the potential to support engineering design and manufacturing of bio-inspired design in the renewable energy sector.

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