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Pathways in Biomimicry to Enhance Solar Technology Capabilities

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Abstract: Efficiency, longevity, and cost-effectiveness in current solar modules are compromised in pursuit of best balancing one another. This report explores the potential of enhancing solar cell practicability through biomimicry. Like solar cells, biological organisms absorb heat during photosynthesis, positioning nature as an inherent source of inspiration to tackle current technological challenges. Significant improvements have been achieved by mimicking structures such as the leaf epidermis for multidirectional light capture, cell membranes for protective encapsulation, and butterfly wings for enhanced light absorption and reflection. For instance, incorporating a BT layer for thermoregulation mimics plant transpiration, enhancing cooling efficiency. Additionally, hierarchical structures inspired by leaf geometry increases angular robustness in both dye-sensitized solar cells and passive emitter and rear cells, and lipid biomolecule interactions shelter halide perovskites from environmental degradation. The nanostructures of butterfly wings also show promise in supporting thin film PVs to overcome conversion inefficiency. Lastly, the reflective properties of butterfly wings have led to advancements in solar concentrators, improving power-to-weight ratios. These examples highlight the untapped potential of biomimicry in furthering the viability and deployment of solar technologies.

Keywords: Biomimicry, Bioinspiration, Biomimetics, Bioreplication, Solar Energy.

1. Introduction

Living organisms exhibit a remarkable range of functionalities, such as efficient light management and adaptive mechanisms. The emulation of such ideas and processes observed in biological systems is known as biomimicry. Borrowing inspiration from nature, biomimicry promotes efficiency and effectiveness in engineering solutions while focusing on the environment and sustainability [1].

Engineered biomimicry can be broken down into three primary modes, with each alluding to a progressively deeper level of imitation. First, bioinspiration implies the application of concepts in nature without copying. For example, helicopters and dragonflies can propel themselves into flight, yet how they do so varies greatly. Second, biomimetics suggest the direct imitation of organisms, specifically their biological functions. Famously, the curvature of the Japanese bullet trains' front end was modeled based upon the shape of birds' beaks to maximize aerodynamics. Finally, bioreplication takes biomimetics a step further by closely recreating natural structures and, when possible, the materials [2].

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Addressing the global energy crisis has become urgent due to the excessive consumption of fossil fuels and the resulting greenhouse gas emissions. Among renewable energy sources, the sun is the most abundant and readily available. Therefore, solar photovoltaic (PV) systems have emerged as a promising solution to energy challenges, and demand for it is only rising. Global PV cumulative capacity stood at 1.6 TW in 2023. Solar energy is expected to represent half of global energy demand's growth between 2024 and 2025 [3].

The viability of solar cell types hinges on the golden triangle: power conversion efficiency, stability, and cost [4]. Silicon-based materials are currently the benchmark for commercial light-harvesting systems, commanding approximately 95% of the market share. Silicon's crystalline structure has enabled a high efficiency of up to 27%, and the booms in production and technological innovation with this material has significantly lowered fabrication costs over the years [5]. While other technologies such as organic solar cells are gaining traction, they have yet to match silicon's high efficiency and scalability. Silicon PVs, however, may be nearing their maximum efficiency as established by Shockley-Queisser limit, which theorizes that silicon's fixed band gap of 1.1 eV prevents an efficiency of over 30% [5]. The recent perovskite-on-silicon tandem solar cells have shown the potential to rival silicon's high efficiency and stability, but scalability remains a challenge [6]. Overall, the market is in need of more options for successful solar technologies.

The intersection between the two—biomimicry and solar technologies—is inevitable as the functions of solar technologies inherently mirror photosynthesis, a biological process where light is absorbed and converted into electrochemical energy. There are three key characteristics of nature which solar devices can benefit from: simplicity, dissipation of heat, and the use of soft matter. Integrating complex mechanisms with versatile designs can instill elegance into solar PVs. As a result of the inability to absorb all incident light, solar devices are prone to increased operating temperatures, which degrade electrical performance and reliability. Additionally, the elasticity of biological tissues can inspire more efficient designs [7].

Engineered biomimicry can provide a framework to guide the enhancement of the efficiency, durability, and cost-effectiveness of solar technologies. This paper explores how biomimicry—through combinations of bioinspiration, biomimetics, and bioreplication—has contributed to different technologies in this rapidly expanding sector and encourages further research into the integration of nature in solar devices.

2. Applications of the Leaf in Solar Technology

Within the typical plant leaf anatomy, vascular bundles (veins), spongy cells, and the epidermis, all of which aid in regulating health and homeostasis, have been pinpointed as structures that can inspire innovation in cell efficiency and stability (Figure 1) [8].

2.1. Vascular bundles and spongy cells

The vascular bundles and spongy cells facilitate plant cooling in a biological process known as transpiration. First, water rises to the leaf from the soil via capillary action and is spread evenly across the leaf surface through vascular bundles. It then diffuses into the extensive intercellular space within the spongy cells. Once warmed, the liquid vaporizes and is expelled through the stroma, releasing heat and preserving the photosynthetic process by stabilizing internal temperatures [8].

Thermal management is a current concern for solar technologies, as unabsorbed incident radiation lowers efficiency and lifespan. There are three existing approaches to decrease heat, but each has its setbacks. Active cooling involves machinery to pump coolant water or air, but such devices require installation costs, regular maintenance, and reductions in net output power. Passive cooling, such as with adding aluminum fins and heat sinks, may be easy and inexpensive; it, however, provides

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minimal performance enhancement due to the low heat transfer rate. Though showing future potential, phase-change material cooling shares the same limitation as passive cooling due to low thermal conductivity [9]. A process like transpiration can guide solar thermal management systems to achieve cooling with simplicity.

Inspired by plant transpiration, Huang et al. applied the concept of water as a coolant to address the high operating temperatures current solar PVs face. They introduced a biomimetic transpiration (BT) layer between a solar cell and a steel wire mesh base. This porous layer, attached to the underside of the cell for thermal contact, consists of natural bamboo fiber bundles surrounded by hydrogel cells (Figure 1). The bamboo fibers, connected to a water tank, are analogous to vascular bundles by uniformly distributing water throughout the 1mm thick device. Formed in an efficient 3D structure, the hydrogel, made of potassium polyacrylate (PAAK), a super absorbent polymer, acts like spongy cells and offers excellent water absorption properties. With the device intact, excess heat is dissipated as water vapor at a transpiration rate similar to that of a natural leaf. Incorporating the BT layer led to a 26ºC temperature reduction and removal of 75% of the excess heat while maintaining a 14% electrical output [8]. This innovation can support the creation of 650 GW of additional power worldwide, nearly 40% more than the current global PV capacity.

Moreover, the model’s low cost and flexibility make the future prospect of this technology realistic. The materials used in the BT layer, bamboo fibers and PAAK, are both eco-friendly and economical. They are commercially popular too, contributing to the model's capital cost being only 2% of a commercial PV panel—1.1 $/m² compared to 55 $/m². The BT model also achieves similar results using seawater. Given the increasing scarcity of freshwater, this attribute cements the BT layer as a worthy cooling solution [8].

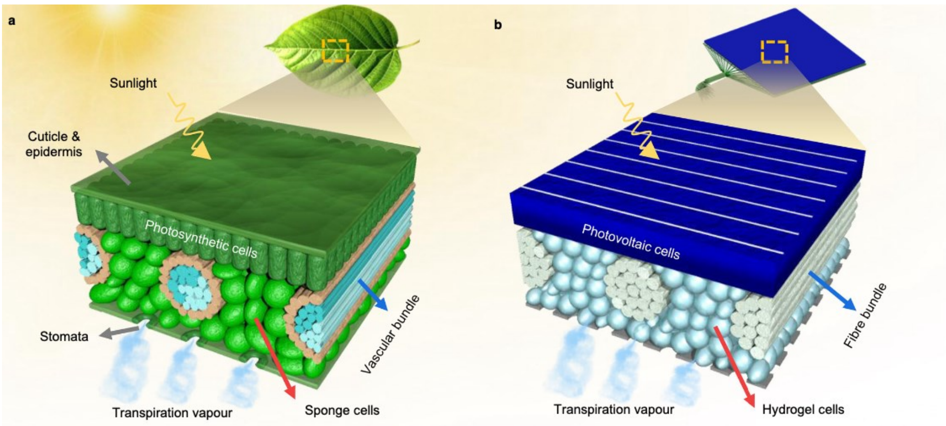

Figure 1: Structure of the anatomy of the leaf and the biomimetic transpiration (BT) layer [8].

2.2. Epidermis

As the first point of interaction between the leaf and incoming photons, the epidermis is indirectly responsible for the dispersal of light into internal structures. The epidermis is also capable of capturing light from all directions [10, 11].

In the solar technology market, bifacial solar cells are the most similar to the leaf epidermis in terms of absorption properties. These modules utilize both the front and rear sides, supporting a 30% increase in power output for large PV systems compared to their traditional monofacial counterparts. This reason and its similar cost to conventional silicon PVs has contributed to this innovative technology’s increasing popularity. However, bifacial solar cells are complex devices; despite their potential, more verification regarding its durability is needed. Previous studies have suggested that structural intricacies make these cells susceptible to deterioration. For example, frameless double-

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glass cells and backside anti-reflective coatings could inadvertently lead to potential induced degradation. While bifacial solar cells are poised for success, gaps in knowledge inhibits their widespread adoption.

Noting the risks in new model designs like bifacial solar PVs, Ju Yun et al. fabricated five light-trapping layers inspired by the different geometries of epidermal cells to achieve panoramic light capture. As the epidermis has evolved into different orientations given the effect of the surrounding environment and individual plant energy needs, Ju Yun et al. developed five morphologies (Figure 2). These light-trapping layers were designed for both dye sensitized solar cells (DSSCs) and passive emitter and rear cell (PERC) solar cells in mind [10, 11].

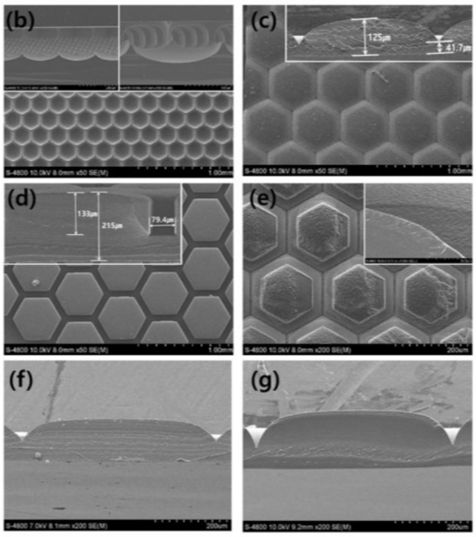

Figure 2: The five proposed morphologies of modified lens arrays: (c) traditional, (d) pillar-shaped, (e) array with rough surfaces, (f) flat, and (g) array with space between patterns [10].

The attachment was made by overlaying polydimethylsiloxane (PDMS) onto an engraved silicon stamp mold. First, the silicon wafer was prepared via photolithography and ultraviolet radiation exposure. Hexagonal shapes were then patterned onto the mold through Bosch and isotropic etching. After cleaning the wafer, PDMS was applied using a spin coater and peeled off upon conforming to the new shape.

Two geometries stood out in different scenarios. Tests with 60º Gaussian-scattered incident light displayed that the lens array layers increased light absorption by 70% compared to standard DSSCs. With scattered light, pillar-shaped arrays exhibited the highest conversion efficiency with vertically incident light and performed well with oblique or scattered light. For varied heights, the pot-shaped array achieved the best results for both vertical (4.33%) and oblique (7.74%) light incidence.

While previous DSSC research has concentrated on optimizing light distribution through structural improvements, expanding the ability to capture omnidirectional light presents a promising direction for future advancements [10].

In contrast, for PERC cells, instead of etching, the master mold is created using an inexpensive process involving silane and ozone treatment. The five structures were formed by adjusting treatment parameters with higher concentrations and extended exposures produced more defined bumps (Figure 3). Compared to a bare PERC device, the PERC cells with the hierarchical structure pattern showed improved efficiencies at oblique angles, particularly at high angle of incidence. Additionally, the custom designs increased wettability, with a wetting angle of 125º indicating maximized light absorption [11].

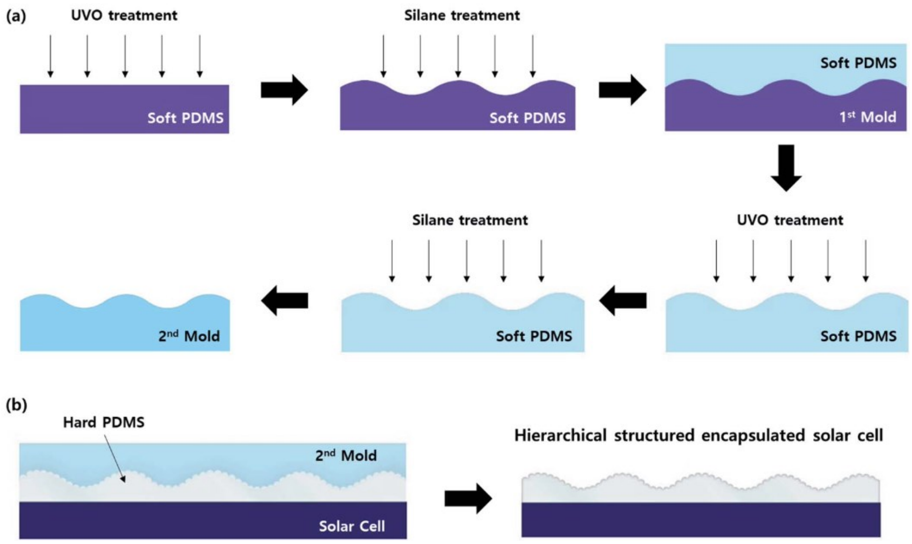

Figure 3: Development process of silicon-based encapsulation for PERC cell. The process involves two distinct procedures: (a) creating the PDMS molds via silane and ozone treatment and (b) casting the mold onto the silicon to achieve desired shape [11].

In terms of next steps, Ju Yun et al. suggest combining the components of the five configurations to further heighten solar PV light sensitivity capabilities.

3. Applications of the Cell Membrane in Solar Technology

Surrounding cells in all living organisms, the cell membrane preserves homeostasis by standing as a line of defense, protecting intracellular compartments from extracellular environments. The cell membrane achieves this function by possessing hydrophilic heads and hydrophobic tails [12].

Inspired by the lipid structure of a cell membrane, Hou et al. designed a micro-emulsion ink capable of rendering into a protective layer for perovskite crystals. Currently, the lack of a protective shell severely hinders the lifespan of halide perovskites: the promising technology can operate for 10 years compared to the average 25. Though lauded for its excellent optoelectronic properties, structural flexibility, and straightforward production, halide perovskites are highly limited by environmental degradation, particularly moisture. Past literature has discussed using a 2D/3D heterostructure bilayer as a viable solution; however, this idea presents risks such as microscale heterogeneities that may compromise net power output. The proposed ink design combines fatty and waxy biomaterials with perovskite precursors. Once in contact with the cell, the perovskite cell absorbs the lipid molecules and a 0D/3D bilayer–in the shape of a bubble–self-assembles [13].

As a precaution, acetonitrile (ACN) and ethanol (EtOH) were used as perovskite precursors. Although solvents such as dimethylformamide (DMF) or dimethyl sulfoxide (DMSO) are more common, DMF and DMSO have a strong affinity for lead ions in the perovskite given their high Gutmann's donor number (DN), leading to competition between precursor and biomolecule binding. Whereas, ACN and EtOH, with a low DN, do not and are therefore suitable for the ink. EtOH can also contain methylamine, a chemical capable of passing into the perovskite lattice and forming a perovskite intermediate cluster (PIC) that increases molecule bonding [13].

Considering these notions, the micro-emulsion ink was synthesized by liquifying powdered EtOH with methylamine using one of two chosen biomolecules (Figure 4). Estrone (E1) and progesterone (PRG) are hydrophobic steroids with a backbone structure of four carbon-based fusion rings and a carbonyl group, enabling strong bonding with lead. Once dissolved, ACN is added to dilute the

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solution. Given that the molecules are immiscible in ACN, the bilayer configuration begins forming, with EtOH and the chosen steroid at the bottom and ACN suspended on top. The bubble fully develops when the two phases are mixed via ultrasonication; the generated kinetic energy triggers the PIC in the molecule to form the micelle-like shapes [13].

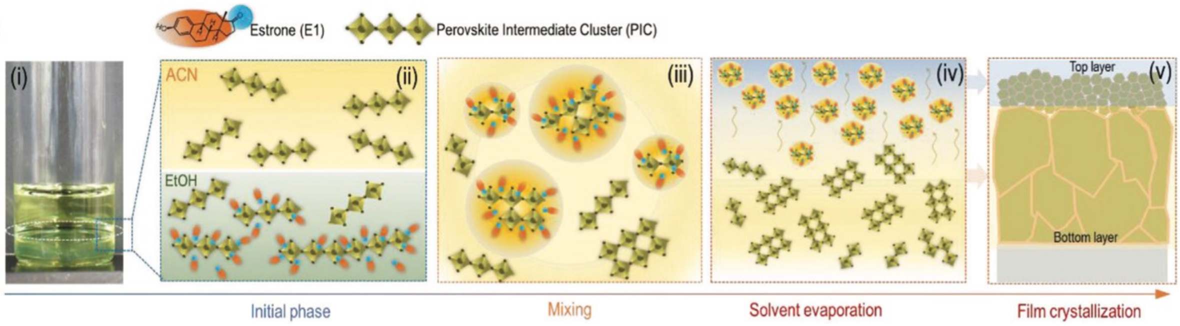

Figure 4: Illustrations of the 0D/3D bilayer structure formation process: (i-ii) initial separated composition of acetonitrile (ACN) and ethanol containing methanol (EtOH), (iii) the integration of the two layers via ultrasonication, (iv) the E1-PIC emulsion bubble begins to form, and (v) the final bilayer structure [13].

The E1 and PRG-based perovskite films displayed enhanced stability and efficiency. They demonstrated prolonged resistance against moisture attacks, with lifespan of the two increasing 18- and 45-fold to 11 and 27 seconds, respectively. They experienced advanced operational stability: 80% of the original PCE value was still retained 4.8 and 5.8 hours later compared to less than an hour for baseline perovskites. These homogeneous layers can also be more effectively upscaled as the model has a smaller area-dependent efficiency drop value of -0.016%cm^{-2} compared to -0.084%cm^{-2} for conventional solar PVs [13].

4. Applications of the Butterfly in Solar Technology

4.1. Common Rose Butterfly

As indicated by the black pigmentation, the wings of the rose butterfly Pachliopta aristolochiae absorb heat through its intricate nanostructured scales and periodic ridges. The nanostructures, which consist of nanoholes suspended from ridges and cross-ribs, capture light across the visible spectrum while leveraging ultraviolet (UV) and near-infrared (NIR) light too. Shorter wavelengths (~350 nm) are absorbed through vertical channeling, where light travels along the ridges' sidewalls towards the nanohole surface for capture. In contrast, longer wavelengths (~850 nm) are absorbed via in-plane scattering, with light dispersing randomly within the rib architecture to increase points of interaction between the photons and absorbing material. For intermediate wavelengths (~550 nm), both channeling and scattering mechanisms are utilized to optimize absorption [14].

Similarities can be drawn between P. aristolochiae wings and thin-film PVs: both are thin photonic structures that are lightweight and flexible. These characteristics allow thin films to stand out as a low cost option for solar technology. However, thin films have historically been restricted by low efficiencies [15]. Past literature has noted that adding textured surfaces could improve thin film efficiency.

Siddique et al. assessed how P. aristolochiae's disordered nanohole arrays can improve thin film light-harvesting by comparing four different orientations of bioinspired thin-film models. Molded with hydrogenated amorphous silicon (a-Si:H), the configurations included one bare slab, an "ordered" array with uniform hole diameters, a "perturbed" array with varying hole diameters, and a

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"correlated" array combining uniform and varied hole diameters, directly mimicking the wings of P. aristolochiae. All three patterned models exhibited over double the absorbance of the reference slab, approximately 64% versus 31.6% in average optical absorptivity, respectively. Moreover, the correlated array retained better absorbance performance when subjected to changing angles of incidence (0º to 80º), with a drop of about 22.8% compared to 27.3% for the ordered structure and 26.8% for the perturbed design [14].

4.2. White Butterfly

As cold-blooded organisms, butterflies rely on the sun for warmth to gain the kinetic energy needed for flight. Unlike many other butterflies, white butterflies in the genus Pieridae, such as P. rapae, tend to fly earlier on cloudy days as they absorb heat easily and quickly. This behavior is due to the unique biostructure of their wings, which contain ovoid granules or "nano-beads" between the gaps in their wing scales. These nano-beads aid in photonic and thermal regulation by containing the white pigment pterin. Pterin absorbs short wavelengths and reflects visible light, while the nano-beads enhance light scattering [16].

Similar to the V-shaped posture butterflies adopt during rest before flight, solar concentrators use a V-trough design using mirrors and lenses to direct light towards a smaller area of PV cells. While solar concentrators are theoretically practical—they reduce energy costs by decreasing required land area and improving efficiency—the various standard designs have drawbacks. Reflective films on plastic mirrors lose reflectivity as surfaces become more complex, specific curved shapes with just a reflective mirror finish are expensive to manufacture, and the effectiveness of vacuum metalizing hinges on the quality of material used. Furthermore, these devices are often bulky and heavy. To advance the development of solar concentrators, taking inspiration from the design of Pieridae butterfly wings can enhance reflectivity [16].

To understand the applicability of Pieridae butterfly wings, Shanks et al. arranged large butterfly wings around a mono-crystalline silicon cell, mimicking how photons are reflected by the wing scales and concentrated at the thorax to ready muscles for flight. A significant increase in power 42.3% was reported, and the power-to-weight ratio improved 17-fold. Two times the amount of light became concentrated at the silicon cell compared to the effects of standard reflective film, and at the optimum angle of 17º, the PV cell's temperature increased by 7.3ºC [16].

Exploring ways to replicate the layer of ovoid pigment through nanofabrication can enhance the reflective properties of solar concentrators and make those technologies more attractive [16].

5. Conclusions

Solar technologies need a new source of inspiration to spur development—though demand for solar technologies is escalating, current limited capabilities leave much to be desired. By emphasizing simplicity, thermoregulation, and soft matter, integrating biomimicry into solar technology designs can effectively address the three pillars of the golden triangle: efficiency, longevity, and cost effectiveness. Mimicking leaf structures, cell membrane characteristics, and butterfly photonic absorption and reflection processes within both additional components and the design models themselves has demonstrated success.

Caused by the inability to absorb all the photons from the sun, overheating decreases cell efficiency and stability. Although current cooling methods exist, they struggle with balancing efficiency and cost. A BT layer can be added to the rear end of a solar PV to provide heat relief by spreading coolant water in a process similar to transpiration, during which plants release heat through water evaporation at the leaf surface. The BT layer incorporates commercially available materials, making this technology accessible and scalable.

Most solar technologies cannot absorb light at multidirectional angles, presenting a major missed opportunity. On the other hand, the complex geometries of the leaf epidermis can do so. Recreating those hierarchical structures on a PDMS layer leads to greater angular robustness for DSSCs and PERCs.

Halide perovskites, a device that excels at light management, lacks an encapsulation layer, posing the risk of environmental damage. The protective shell can be likened to the cell membranes that surround all living cells: both safeguard the internal from the external. A cell membrane can be replicated by exposing lipid biomolecules to perovskite precursors. An emulsion bubble then forms as the two interact atop a perovskite crystal, which successfully defends the cell from moisture.

Thin film PVs and the wings of P. aristolochiae butterflies have been compared given their similar thin widths. The one stark difference is that thin films are known for their conversion inefficiency, while the nanostured scales in P. aristolochiae wings allow a high degree of solar capture. Given their paralleling appearances, the wings of P. aristolochiae can be further examined to improve thin film efficiency.

Although various solar concentrators exist, each has its own compromises, especially with regards to material quality and cost. Solar concentrators can draw inspiration from white Pieridae wings given their similar V-shaped arrangement. Given that these wings allowed more light to be centralized on the cell and improved the power-to-weight ratio by 17-fold, they may provide solutions to the current related challenges.

These examples highlight just a few of the many potential applications of biomimicry that have yet to be fully realized. Therefore, prioritizing the fusion of biomimicry in solar technology designs is advantageous towards facilitating the expansion of solar energy.

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