Bionic Engineering Based on Plant Characteristics and Human Adaptive Specificity to the Environment

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Abstract. After a long evolutionary process, plants have developed unique mechanisms for energy utilization, structural optimization, water control, and environmental adaptation. These characteristics not only maintain the stability of the Earth's ecosystem but also provide bionic inspiration for humans to address environmental challenges. Focusing on the topic of "implementing bionic engineering based on plant characteristics to adapt to the human environment", this paper deeply analyzes the application potential of plant characteristics in energy systems, architecture and materials, water resource management, and medical engineering. It further discusses the significance of plant characteristics for human adaptation to extreme climates, urban environments, space and marine environments, as well as healthy lifestyle. Within this framework, the paper proposes the future development direction of bionic engineering, particularly emphasizing the value of interdisciplinary integration, intelligent planning, and sustainable development strategies. Relevant studies have shown that plant bionics is conducive to promoting the development of green technology and environmental engineering, meanwhile providing new theoretical basis and operational approaches for humans to achieve the goal of harmonious coexistence with complex environments.

Keywords: plant characteristics, bionic engineering, environmental adaptation, sustainable development, interdisciplinary integration.

1. Introduction

Plants are among the most common and ancient organisms on Earth. Over the evolution through hundreds of millions of years, they have gradually developed extremely complex yet highly efficient environmental adaptation systems [1]. Plants utilize solar energy precisely through photosynthesis and absorb water as well as nutrients precisely via their root structures, possessing strong adaptability in aspects such as morphology, epidermal structure, and metabolic pathways [1]. For instance, cacti in deserts survive in extremely arid environments by virtue of their unique fog-collecting and water-storing structures. Plants in tropical rainforest maintain energy balance in high-temperature and high-humidity environments depending on their large leaves and stomatal regulation mechanisms [2]. Plants in frigid zones resist damage from extreme low temperatures with the help of antifreeze proteins and metabolic regulation. These characteristics not only make plants a crucial support for maintaining ecological balance but also provide humans with abundant bionic inspiration to address the challenges of complex environments.

Nowadays, human society is confronted with major issues such as global climate change, energy shortage, urbanization expansion, and ecological degradation. When dealing with these problems, traditional engineering technologies usually present limitations including high energy consumption, low efficiency, and secondary damage to the environment. With the development of science and technology, bionic engineering has gradually become a frontier field of interdisciplinary research. It creates new technologies and devices by imitating the functions and structures of natural systems. The energy conversion mechanisms, mechanically optimized structures, and environmental response patterns contained in plant characteristics provide natural reference models for bionic engineering. Therefore, bionic engineering based on plant characteristics is not only a key approach to exploring the laws of nature, but also a crucial direction for promoting humans to achieve environmental adaptive specificity and sustainable development.

The research method of this paper is primarily based on a status analysis. First, it systematically reviews the unique mechanisms of plants in energy acquisition, material cycling, and environmental adaptation, and summarizes their representative survival strategies in different ecological environments. Second, it analyzes and compares current studies and applications in plant-inspired bionic engineering, discussing their theoretical value and practical potential. The purpose of this study is to comprehensively summarize the adaptive wisdom of plants, reveal its inspiration for bionic engineering and sustainable development, and promote cross-disciplinary integration of botany, engineering, materials science, and environmental science. In doing so, it aims to provide a foundation for building a theoretical system of bionic engineering and to highlight practical applications in areas such as clean energy development, green building materials, and water resource management.

2. Bionic Inspiration from Plant Characteristics

2.1 Photosynthesis and Energy Utilization

Plants efficiently utilize solar energy through photosynthesis, which provides direct inspiration for the development of new energy conversion technologies [3]. Currently, artificial photosynthesis has become a popular research direction. The key lies in using photosensitive materials and catalysts to mimic the energy conversion process of chloroplasts, converting water and carbon dioxide into clean fuels such as hydrogen and methanol [3]. In recent years, photoelectrocatalytic systems based on nanomaterials have gradually matured. Light-harvesting films that mimic the stacked structure of chloroplasts can significantly improve light absorption efficiency, and transition metal complex catalysts have shown almost the same efficiency as natural photosystems in water-splitting reactions [4].

Beyond artificial photosynthesis, the wisdom of plants in energy storage and distribution also provides ideas for the improvement of energy systems [4]. Some research teams have adopted bionic porous materials to design new battery electrodes. The design of these materials is based on the vascular network of xylem, enabling rapid electron and ion transfer and thus improving energy storage efficiency. What is more, the principles of energy consumption and regulation in the plant photoprotection mechanism have also been applied to photovoltaic cells to prevent their efficiency from decreasing under high light intensity. Thus, bionic energy systems developed based on plant characteristics might resolve the dependence on fossil energy and offer technical support for the carbon neutrality strategy.

2.2 Structure and Mechanical Properties

After a long period of development and evolution, plants have developed a variety of distinct structures and mechanical properties. Cellulose and lignin in plant cell walls construct a hierarchical structure, which possesses mechanical advantages from the nanoscale to the macroscale [5]. This optimization not only improves compression and bending resistance but also endows plants with adaptability under external stresses such as wind force and snow pressure. In recent years, materials scientists have used tools like scanning electron microscopes to analyze the microscopic structure of plants and applied these findings to carbon fiber composites and bionic lightweight steel [5]. Prominent examples are the special structures of plants like lotus leaves and pinecones. The former has superhydrophobic surface mechanical characteristics, while the latter uses the orientation of fibers to achieve a morphology that changes with humidity. These examples show that plant structures not just to embody the engineering optimization concept of "lightweight-high strength" but to provide directions for the development of intelligent materials and renewable structures.

2.3 Plant Moisture and Gas Regulation

The effective regulation of moisture and gas is a crucial ability for plant survival, especially under arid, humid, or extreme climatic conditions. Plants rely on the varying depths of root distribution to maximize water absorption and adjust the transpiration of leaves through the opening and closing of stomata, thereby maintaining a balance between water loss and carbon dioxide intake. In this process, the regulation mechanism of stomata is remarkably ingenious: when the external environment is arid, stomata will be closed to reduce transpiration, while under suitable conditions, they will be opened up to enhance photosynthesis [6].

A typical bionic application lies in the research on cacti and succulents. The characteristics of cactus spines, including reducing the transpiration area, condensing atmospheric moisture in the early morning and evening, and guiding it to the roots via capillary action, have been applied to fog-harvesting devices in arid regions [6]. The superhydrophobic structure of lotus leaves, which enables rapid water drainage and self-cleaning, has inspired the development of self-cleaning glass and waterproof fabrics. Additionally, the high efficiency of plant gas exchange has provided insights for air purification and carbon capture. Artificial stomatal materials are being developed to mimic plants' mechanism of regulating gas flux, aiming to create breathable textiles or indoor air control systems. It can thus be seen that the mechanisms of plant moisture and gas regulation go beyond embodying the wisdom of ecological adaptation to driving human innovation in environmental engineering and resource management.

2.4 Environmental Response and Self-Adaptability

Plants are not mere ecological members as they can respond to the environment through complex sensing and regulatory mechanisms. The most common examples are phototropism and geotropism: plants can perceive light intensity and the direction of gravity, thereby adjusting their growth orientation to secure optimal survival conditions. Some plants are even capable of rapid movements [7]. For instance, the leaves of Mimosa pudica (sensitive plant) close immediately upon being touched, and Venus flytraps use mechanical receptors to close their leaves and capture insects. These adaptive movements demonstrate plants' highly efficient integration capabilities in signal perception, energy allocation, and structural transformation.

In bionic engineering, these characteristics are widely applied in intelligent materials and flexible robots. For example, bionic driving materials are used to mimic the osmotic pressure changes in plant cells, enabling automatic deformation without an external power source, which has further led to the development of adaptive robots that can operate in complex environments. The opening and closing mechanism of pinecones has inspired the design of humidity-responsive materials, which are used in passive ventilation systems and self-adaptive building components. Moreover, plants' environmental responses are frequently linked to ecological interactions, such as signaling mechanisms like odor emission and color change, which have provided new inspiration for the design of sensors and communication devices. In a word, the environmental response and self-adaptability of plants extend beyond reflecting how living organisms cleverly adapt to the environment to offering numerous references for the survival and development of future artificial systems in extreme environments.

3. Human Environmental Specific Adaptation Strategies

3.1 Extreme Climate Adaptation

As global climate change becomes increasingly severe, the issue of human survival and development in extreme environments has grown more evident. Over the long course of evolution, plants have developed special adaptive mechanisms to cope with extreme climates such as extreme cold, intense heat, and drought, providing humans with bionic inspiration. For instance, cold-region plants synthesize antifreeze proteins and carbohydrates to prevent the formation of ice crystals inside cells, which can be applied to the frozen preservation of food and the long-term storage of biological samples. The principle that desert plants relying on collenchyma, water-storing cells, and stomatal regulation to survive in extremely water-scarce environments for extended periods, provide support to drive the development of low-energy-consumption water collection and storage devices in desert areas.

From the engineering perspective, bionic building materials and clothing have been designed to resist extreme climates [8]. Heat-dissipating and radiation-shielding materials that mimic the microstructures of cactus epidermis can help humans maintain a comfortable environment in high temperatures. The thermal insulation materials modeled on the basis of the fiber layer structure of polar mosses can provide efficient thermal protection in extreme cold. Additionally, the dynamic environmental adaptation characteristics of plants—such as phototropism, where they adjust leaf angles based on light intensity—can also inspire the design of smart building windows and exterior walls, enabling them to automatically regulate heat and light according to external conditions. Therefore, bionic strategies developed based on plant characteristics not only enhance human survival capabilities in extreme climates but also provide theoretical and operational support for the creation of sustainable living environments.

3.2 Urban Environmental Adaptation

With the advancement of urbanization, population density has increased. Moreover, the consumption of energy has increased and pollution has been intensified. The method to achieve harmonious coexistence between humans and the urban environment has become an urgent task. The characteristics of plants in purifying air, regulating temperature, and mitigating noise have provided ideas for urban adaptive design. For example, plant leaves can efficiently adsorb particulate matter and reduce carbon dioxide levels through photosynthesis, leading to the development of air filtration systems that mimic biological materials, which hold application prospects in urban transportation and indoor environmental management.

In alleviating the urban heat island effect, the transpiration and shading effects of plants play a crucial role. Bionic engineering mimics the water transpiration mechanism of plants to develop building exterior wall and roof coatings capable of active cooling, significantly reducing energy consumption. The hierarchical structure of plant communities in noise buffering has inspired the design of bionic sound insulation barriers, allowing cities to maintain a relatively quiet environment even in busy traffic areas. Additionally, the soil-fixing and purification functions of plant roots have provided models for urban rainwater management and the construction of green infrastructure. Permeable pavements and bionic drainage systems, which are designed based on the structure of plant roots, have enhanced cities' ability to cope with heavy rains and flood disasters. It can be said that the diverse functions of plants provide practical bionic approaches for the construction of future "sponge cities" and "smart cities".

3.3 Space and Marine Environment Adaptation

One of the goals of human's future development is to break through the limitations of Earth and explore extreme environments such as space and the ocean. However, these environments pose challenges like high radiation, low oxygen levels, water scarcity, or extreme pressure. The survival methods of plants have provided some inspiration for human exploration. Alpine plants store substances that can absorb ultraviolet rays, enabling them to resist radiation, which can serve as a reference for the development of protective materials for spacesuits and space stations. Deep-sea plants and algae can survive in dimly lit or completely lightless environments through special pigments or chemical energy conversion, which provides insights for the development of deep-sea energy utilization and life support systems.

In the space, the closed-loop cycling capability of plants is particularly important. Through photosynthesis, plants produce oxygen and absorb carbon dioxide, making them a key component of the life support systems for future space habitats. Currently, the International Space Station has already conducted plant cultivation experiments to study the growth of plants in a microgravity environment [9]. The ability of plants to survive through anaerobic metabolism under oxygen-deficient conditions has provided ideas for designing emergency oxygen supply systems in space and submarines. In terms of marine adaptation, the salt-filtering function of mangrove roots provides a bionic model for seawater desalination, and the efficient photosynthetic mechanism of algae has been applied in marine carbon sequestration and ecological restoration projects. It can be predicted that the application of plant characteristics in adapting to space and marine environments will become an essential guarantee for human's cross-domain survival and development in the future.

4. Discussion

Bionic engineering inspired by plant characteristics is developing rapidly, reflecting the increasing importance of bioinspired strategies in addressing global challenges. At present, research is largely centered on reviewing and analyzing how plants achieve energy conversion, structural optimization, water and gas regulation, and adaptive responses to extreme environments. These studies highlight the extraordinary evolutionary wisdom of plants, which have developed efficient survival mechanisms across deserts, rainforests, and polar regions. Looking forward, the future of plant-based bionic engineering will rely more heavily on interdisciplinary integration and technological innovation. Advances in nanotechnology, artificial intelligence, and synthetic biology will enable more precise imitation of plant functions, such as photosynthetic energy utilization, dynamic environmental responses, and the biosynthesis of functional substances. These developments will likely give rise to high-efficiency bionic systems that extend beyond the traditional domains of energy and materials science. Potential applications include smart, self-regulating buildings inspired by plant adaptive mechanisms, innovative medical rehabilitation technologies, and solutions tailored for survival in extreme environments, including extraterrestrial exploration. Although significant progress has been achieved, the field still faces challenges such as technological complexity, high costs, and ethical considerations. Overcoming these barriers will require sustained interdisciplinary collaboration and a careful balance between innovation and responsibility.

5. Conclusion

This study highlights the remarkable adaptive strategies that plants have evolved over millions of years—ranging from efficient solar energy utilization, hierarchical structural optimization, to sophisticated mechanisms for water and gas regulation, and environmental responsiveness. By systematically analyzing these biological features, the research underscores how plant-inspired bionic engineering can provide powerful insights for addressing contemporary global challenges, including energy scarcity, urban sustainability, and adaptation to extreme environments on Earth and beyond. Current developments, such as artificial photosynthesis, bionic structural materials, fog-harvesting devices, and bioinspired adaptive systems, illustrate the vast potential of integrating botanical wisdom with engineering innovation.

However, the study has certain limitations. It primarily relies on status analysis and existing literature, with limited empirical validation or experimental data to verify the feasibility and efficiency of plant-inspired designs. Future research could advance in several directions. Interdisciplinary collaboration between botany, materials science, environmental engineering, and information technology is essential to transform biological insights into practical and scalable applications. More empirical studies and experimental validations are needed to assess the efficiency, sustainability, and adaptability of plant-inspired technologies in real-world contexts.

References

[1] Willis, K. J., & McElwain, J. C. (2014). The evolution of plants. Oxford University Press.

[2] Yetman, D. (2007). The great cacti: ethnobotany & biogeography. University of Arizona Press.

[3] Wang, Z., Hu, Y., Zhang, S., & Sun, Y. (2022). Artificial photosynthesis systems for solar energy conversion and storage: platforms and their realities. Chemical Society Reviews, 51(15), 6704-6737.

[4] Wu, H., Zhang, D., Lei, B. X., & Liu, Z. Q. (2022). Metal oxide based photoelectrodes in photoelectrocatalysis: advances and challenges. ChemPlusChem, 87(5), e202200097.

[5] Koshani, R., Pitcher, M. L., Yu, J., Mahajan, C. L., Kim, S. H., & Sheikhi, A. (2025). Plant cell wall-like soft materials: micro-and nanoengineering, properties, and applications. Nano-Micro Letters, 17(1), 103.

[6] Chaves, M. M., Costa, J. M., Zarrouk, O., Pinheiro, C., Lopes, C. M., & Pereira, J. S. (2016). Controlling stomatal aperture in semi-arid regions—The dilemma of saving water or being cool?. Plant Science, 251, 54-64.

[7] Sisodia, R., & Bhatla, S. C. (2018). Plant movements. In Plant physiology, development and metabolism (pp. 907-935). Singapore: Springer Nature Singapore.

[8] Yuan, Y., Yu, X., Yang, X., Xiao, Y., Xiang, B., & Wang, Y. (2017). Bionic building energy efficiency and bionic green architecture: A review. Renewable and sustainable energy reviews, 74, 771-787.

[9] Liu, H., Yao, Z., Fu, Y., & Feng, J. (2021). Review of research into bioregenerative life support system (s) which can support humans living in space. Life sciences in space research, 31, 113-120.