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Review Article

FUTURE PROJECTIONS WITH PLANTS THAT BUILT OUR PAST

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ABSTRACT. Autotrophy is the fundamental process of the origin of life. A major chemical transformation occurred in the atmosphere after the Great Oxidation Event, which *Cyanobacteria* initiated through photosynthesis. Since the evolution of Embryophytes 568-815 million years ago, it is clear that plants have entirely transformed the planet. Their impact extends from global biogeochemical cycles to the creation of habitats. Over millions of years, plants have exhibited adaptive traits that contribute to their sustainability, which have developed in response to evolutionary selection pressures. Solutions refined and developed by nature are a constant source of inspiration for designers and engineers, and the practice of drawing inspiration from nature as a source of innovative designs is referred to as "biomimicry". In this review, we will consider some topics that we can draw inspiration from plants, including secondary metabolites, superhydrophobic surfaces, condensation of air humidity, communication between plants and other organisms, and briefly examine plantoids.

Keywords: bio-inspired, biomimicry, plantoid, wood-wide-web

PLANT EVOLUTION AND ECOLOGICAL FUNCTION

Autotrophy is the fundamental process of the origin of life. Photosynthesis, indispensable for our life, is dependent on an oxygenated atmosphere and plant biomass and is initiated by photons from the sun, stimulating electrons in chlorophyll. When a particle of light hits a chlorophyll molecule, an electron jumps off the molecule and rises to a higher energy level. In an instant, it returns to its previous energy state. All life on Earth depends upon the instantaneous energy the electron gains [1,2]. A major chemical transformation occurred in the atmosphere after the Great Oxidation Event, which *Cyanobacteria* initiated through photosynthesis. Atmospheric oxygen concentrations approached the present atmospheric levels (PAL) using the Great Oxidation Event that occurred *c.* 2.4 billion years ago [3] and Neoproterozoic Oxidation Event (NOE) *c.* 800–600 million years ago [4]. According to molecular clock analyses, it is now estimated that Embryophytes evolved 568-815 million years ago and Angiosperms evolved 175-240 million years ago [5,6].

Over millions of years, plants have exhibited adaptive traits that contribute to their sustainability, which have developed in response to evolutionary selection pressures. Adaptive traits provide a fitness advantage in a given environment [7]. Plant growth and ecosystem primary productivity are ultimately dependent on photosynthesis [8]. Photosynthesis provides the basis for all life since it drives the great cycles of CO_2 uptake and O_2 evolution [9]. Plants have entirely transformed the planet. Their impact extends from global biogeochemical cycles to the creation of habitats [5] and supports biodiversity and ecosystem multifunctionality [10].

Thanks to their symbiotic relationships with fungi and bacteria, they recycle minerals such as C and N through decay [11]. They also keep the ecosystem clean by absorbing heavy metals and pollutants from soil and water [12].

From our perspective, photosynthesis is a giant leap in the history of life on Earth and also seems to be the primary key to our future life on Earth and other planets. As humans, we have been benefiting from the various features of plants for centuries. Nutrition, clothing, shelter, hunting tools, land and water transportation, and medicine production were among the first areas of use.

PRINCIPLES AND DEFINITIONS OF BIOMIMICRY

In addition to their areas of use in human history, it is possible to adapt plants to technology by drawing inspiration from their survival and adaptation mechanisms. For example, thanks to plants showing that solar energy can be converted into other energies, solar panels have been made, and electrical energy has been obtained. Even efforts are being made to convert solar energy into chemical energy through artificial photosynthesis technologies [13]. Solutions refined and developed by nature are a constant source of inspiration for designers and engineers, and the practice of drawing inspiration from nature as a source of innovative designs is referred to as "biomimicry - biomimetic" [14].

Biomimicry represents the application of principles inspired by evolutionary adaptations observed in nature. Human-designed systems often depend on trial-and-error approaches that carry time, cost, and energy loss risks. However, nature has already optimized solutions through evolutionary processes. [15]. In nature, every organism, process, and system operates with remarkable efficiency in resource use. At the same time, this efficiency is consistently maintained from the cellular components of organisms to ecosystems. Holism enables the propagation of successful strategies throughout these entire systems [16].

As we uncover the mysteries of the functional properties that plants acquire in response to their interactions with the environment and other organisms, we aim to adapt these properties to human life. By exploring the remarkable mimicry behaviours observed in the plant kingdom and the physiological and genetic mechanisms underlying these behaviours, technologies applicable to human use are being developed.

CASE STUDIES OF BIO-INSPIRED TECHNOLOGIES

Water Collection Systems

Plants and animals living in the world's driest regions have unique chemistry and structures on or inside their bodies for collecting and transporting water. Many plant and animal species in the arid areas demonstrate effective solutions for collecting water from fog [17]. For example, some succulents tend to have structures that help trap atmospheric moisture when the air gets cold in deserts at night. *Opuntia microdasys* is a cactus species that collects water through clusters of conical spines, each bearing oriented barbs and grooves (Fig. 1) [18]. Water droplets from saturated fog are collected at the tips of the barbs. When the droplets reach a critical size, they move towards the base of the conical spine. When drops come into contact with the trichomes at the base of the spines, the plant quickly absorbs the water drops.

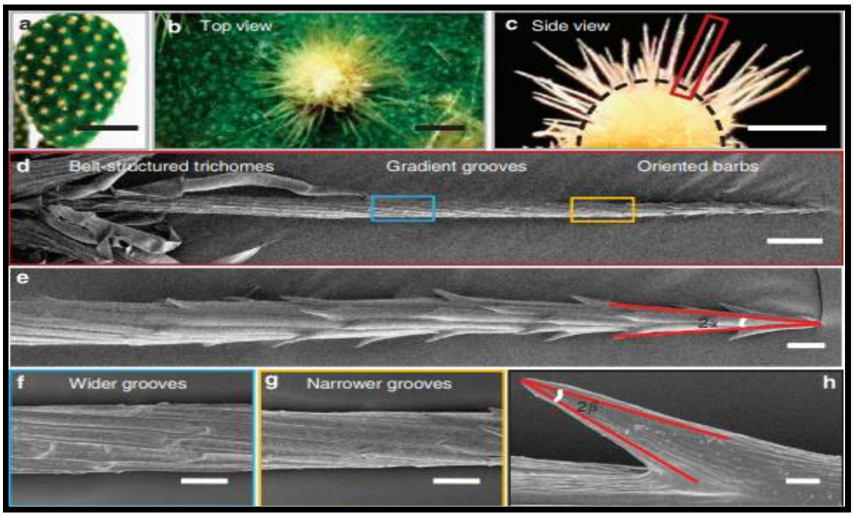

Fig. 1. *Appearance and surface structures of the cactus. (a) Optical image of a plant of O. microdasys stem covered with well-distributed clusters of spines and trichomes. (b,c) Magnified optical images of a single cluster with spines growing from the trichomes in the top (b) and side (c) views. (d) SEM image of a single spine divided into three regions, the tip (e) with an apex angle (2α) and oriented barbs, the middle (f,g) with gradient grooves, and the base with belt-structured trichomes. (f,g) Magnified images of regions near the base and tip of the cactus spine, respectively. The microgrooves near the base are wider and sparser than those near the tip. (h) Magnified image of a single barb with an apex angle (2β) covering the tip of the spine (e). Scale bars, 5 cm (a), 500 mm (b,c), 100 mm (d), 20 mm (e–g), and 2 mm (h). [18]*

The mechanisms underlying the cactus's efficient fog collection system include Laplace pressure, the gradient of surface-free energy, and integrating multiple functional components. The gradient of the Laplace pressure between the two sides causes the water drops on the barbs to move continuously towards the base of the barbs. The gradient in surface-free energy acts as a driving force, guiding the collected water droplets from the tip toward the base. Understanding the structure–function relationship involved in this fog collection process can be an inspiration for designing novel materials and devices to harvest drinking water from fog [18]. Designed by architect Arturo Vittori, Warka Water Tower (Fig. 2) is a technological and sustainable example of water collection and condensation systems. Its daily capacity is an average of 100 litres of water from atmospheric humidity [19, 20].

Fig. 2. *Warka Water Tower, version n. 4 constructed in Cameroon (https://warkawater.org/warkatower/)*

Surface Engineering (Superhydrophobicity)

Superhydrophobic surfaces (SHPOS) play an essential role in various industrial applications. The surface is known to be superhydrophobic when the water contact angle is larger than 150° [21]. The famous Wenzel and Cassie-Baxter models have been proposed to understand the correlation between the surface roughness and wettability. In the case of the Cassie-Baxter model, the liquid drop sits on the top asperities of dual-scale surface structure, and air is supposed to be trapped in the rough structure underneath the liquid, which gives a high-water contact angle (Fig. 3) [21].

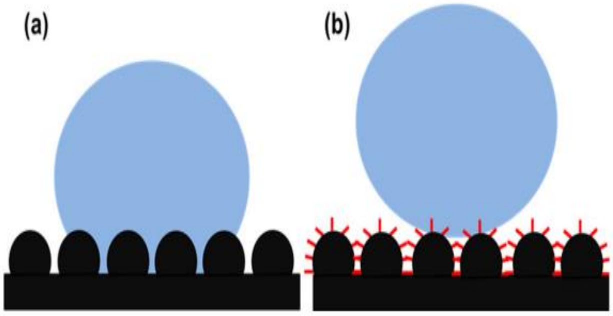

Fig. 3. *A schematic showing the behaviour of a water droplet on a rough surface in (a) Wenzel's and (b) Cassie-Baxter's state. [21]*

The superhydrophobic surfaces created by the egg-beater-like leaf hairs of *Salvinia* and the slippery surface of *Nepenthes* are combined with an engineering design, offering bioinspiration for various applications requiring the reduction of fluid resistance [22]. This inspiration can be used to prevent dangerous freezing on aircraft wings and friction of the ship's hull with water during navigation. Reducing surface fouling thanks to the presence of the air layer can realize a range of ecological and economic benefits.

Biomimetic Adhesion

Throughout evolution, various plants have developed hook-like structures on various organs that facilitate interlocking with animal fur and feathers. These hooks, often found on fruits or seeds, are necessary for their dispersal. Understanding the mechanical properties of these structures is essential for elucidating the underlying dispersal mechanism. Furthermore, the geometrical parameters of the hooks are critical for determining the efficiency of their interaction with animal hair and feathers [23]. A Swiss electrical engineer named George de Mastral examined the fruits of the *Geum urbanum* L. (Rosaceae) (Fig.4) plant that stuck to his dog's fur in 1941. Observing that the fruits could adhere effectively to hairy surfaces via their backward-curved hooks, he developed the hook-and-loop fastener (Velcro®), which is now widely used daily. [24].

Fig. 4. *Fruits of Geum urbanum (https://floraveg.eu/taxon/overview/Geum%20urbanum)*

Secondary Metabolites and Plant Communication

Plant-derived chemicals are among the earliest plant-based materials adapted for human use, with their application dating back to primitive tribal societies. Today, it is known that the therapeutic properties of plants originate from the secondary metabolites they produce. In fact, plants do not make these secondary metabolites as remedies for humans, but rather for a variety of ecological and physiological purposes, such as defence mechanisms against pathogens and herbivores, interaction with other organisms, interspecies competition, attracting pollinators, and protecting from ultraviolet light [25].

In addition to their roles within the plant, secondary metabolites are also known to serve as signalling molecules that warn neighbouring plants of herbivore threats. For example, the ethylene gas released by the plant when an herbivore bites it creates a warning signal to pump the toxin into neighboring trees' leaves [19, 26, 27]. Similarly, in the experiment conducted by Karban et al. [28], wild tobacco plants (*Nicotiana attenuata*) adjacent to clipped sagebrush (*Artemisia tridentata*) were found to have increased levels of the defensive oxidative enzyme polyphenol oxidase, relative to control tobacco plants adjacent to unclipped sagebrush. Tobacco plants next to clipped sagebrush have significantly reduced leaf damage by grasshoppers and caterpillars compared to unclipped controls over three field seasons.

Salicylic acid, a compound produced by the willow tree and traditionally used by humans as an analgesic and antipyretic, is an essential component of the plant’s defence system. [29]. Alkaloids, a class of secondary metabolites, are known to be psychoactive compounds that influence brain function [30]. Intriguingly, plants invest energy in producing such addictive molecules that target animal physiology. For example, extrafloral nectar structures found in some plants serve to attract ants [31]. However, along with this nectar, many chemical molecules such as alkaloids and GABA (γ-aminobutyric acid) are also given to the ants. These molecules, which create an inhibitory neurotransmitter effect in the animal's brain, encourage the ants to attack harmful herbivores. Thus, the plant attracts and addicts the ants with sweet and alkaloid-rich nectar, then controls their behaviour by increasing their aggression and mobility in the plant. All this is achieved by altering the quantity and quality of neuroactive substances found in the nectar. Animals are chemically manipulated by plants rooted in the ground and thought to be defenceless and passive [19, 32].

Furthermore, secondary compounds are economically crucial for humans in pharmaceuticals, nutraceuticals, food additives, and agrochemicals. Therefore, various strategies have been explored to enhance their production and accumulation in plants [33]. Secondary metabolite production can be induced in vitro by treating plant cell cultures with biotic or abiotic elicitors and signalling molecules [34], thereby enhancing the overall yield of these compounds. To establish a more efficient and holistic approach for the discovery of medicinally active secondary metabolites, integrating the fields of ecological (physiological and chemical) research and pharmacology is recommended. Such integration sheds light on how herbivores have evolved to utilize these compounds and enhances our understanding of their medicinal properties [35].

Endophytic fungi are essential in increasing plants' defence effectiveness against herbivorous animals and infections by pathogenic microorganisms [36]. It is hypothesized that endophytic fungi, as protective agents, produce numerous bioactive secondary metabolites and induce physiological changes in the infected host plant, further stimulating the immune system [37, 38]. Various experiments on endophytic fungi and their interactions with host plants have demonstrated that these fungi promote the host's defence mechanisms by synthesizing bioactive secondary metabolites. [39]. Another way an endophytic fungus benefits the host plant is that endophytic fungi promote plant growth by producing phytohormones, including cytokines, auxins, and gibberellins [38].

The distribution of secondary metabolites such as ethylene, released by herbivore-attacked host plants to warn neighbouring plants, plays a critical role in population- and community-level plant defence. However, the transmission of gaseous molecules like ethylene through the air is slow and limited in range. Fungal hyphae facilitate the transfer of resources and signalling molecules by forming underground connections between plants, effectively acting as an underground communication system. These extensive fungal networks are dubbed the 'Wood Wide Web (WWW) [40].

Mycorrhizal fungi, which belong to the endophytic fungi family, establish symbiotic relationships with the roots of over 90% of plant species [41]. In the study conducted by Touseef [40], resource allocation in dye-injected trees was monitored through mycorrhizal networks, and it was determined that resources were transferred from the “mother trees” to the developing seedlings within 48 hours. DNA sequencing identified a single fungal genotype of *Laccaria* sp. colonizing the roots of all Douglas fir trees within our 30 x 30 m forest plot, demonstrating a contiguous mycelial network [40]. The underground social network interconnecting trees through mycorrhizal fungal linkages holds great promise for transforming ecological understanding and unlocking nature’s innovations for practical application [40].

Plant-Inspired Robotics (Plantoids)

Among the primary advances that plants and sessile animals made to survive against predation was the evolution of different modular structures. Roots, leaves, branches, shoots, buds, and flowers are repeated many times during the development of a single plant body. Thus, some modules of the body can survive and regenerate the individual plant in case of environmental damage or predation [42].

Modularity, reiteration, and evolved sensing systems represent some of the most critical challenges in contemporary robotics [42]. Aiming to develop machines capable of desired movement, perception, and cognition, robotics is increasingly drawing inspiration from plant systems, particularly in developing soft robots. Soft robotics primarily relies on using soft materials, enabling the creation of adaptable and resilient structures [43]. This emerging field presents challenges and opportunities for revolutionizing robotics and exploring new materials and fabrication techniques [44].

Despite plants being seen traditionally as passive entities, in reality, they are able to grow, move, sense, and communicate [45]. From a technological point of view, plants present interesting characteristics, such as:

- Capacity for directional growth and exploration/monitoring in response to external stimuli.
- Osmotic actuation principle, used for plant cell elongation.

- Sensitivity to a vast range of different physical and chemical stimuli both in the aerial and in the underground part;
- Efficient use of energy resources with optimization of source-sink relationship [46].

These characteristics can be a source of inspiration for the realization of several technological systems, such as:

- Innovative robotic probes, with thrusting capabilities for reducing the energy consumption during the soil penetration.
- New classes of actuators with very low power consumption, high modulation actuation capability, slow actuation, and high force/pressure actuation.
- New sensor fusion algorithms that permit driving the root growth properly
- New strategies for energy use optimization.
- New communications techniques and strategies based on distributed intelligence [46].

Plant robots are designed inspired by the behaviour of plants. Plantoids contain root and shoot systems being able to change its geometric configuration and size according to environmental conditions and can be divided in three main sub-systems: (1) a main body, carrying batteries, electronics and radio systems; (2) the root system, with electro-osmotic actuators; (3) the root apex, with sensors (Fig. 5) [42].

Fig. 5. *The plantoid: a bioinspired robot developed at the Italian Institute of Technology, Pisa, Italy, by The Plantoid Project led by Barbara Mazzolai. © Bioinspired Soft Robotics Lab, Italian Institute of Technology, Pisa, Italy.*

Plantoids are designed to move slowly, explore their environment efficiently, and exhibit high actuation forces with minimal power consumption by imitating plant strategies. The apex of the plantoid is capable of growth and penetration into the soil while simultaneously gathering data from other apexes through plant-to-plant communication. This architecture enables the use of distributed intelligence strategies unique to the plant kingdom [46]. These features of the plantoids make them particularly well-suited for operating in unpredictable, complex, and hazardous environments. Plantoids can be employed in agriculture to monitor soil conditions, root development, and nutrient distribution. Their ability to grow and sense underground makes them particularly valuable for agriculture and sustainable farming practices. In the field of earth sciences, plantoids offer novel tools for investigating soil composition and exploring inaccessible terrains. Furthermore, their energy-efficient and adaptable structures make them promising candidates for autonomous missions in extraterrestrial environments, where conventional robotic systems may struggle to operate effectively.

CONCLUSION AND FUTURE PROSPECTS

Biomimicry refers to drawing inspiration from the structure and functioning of natural organisms and applying these principles to technological innovation. In plant-based technologies, biomimicry facilitates the incorporation of plants' adaptive capabilities, energy efficiency, and environmentally sustainable design strategies into human-made systems. Advances in biotechnology are expected to make significant contributions to improving human life and developing future technologies.

Designers can draw upon biomimicry and insights from supporting scientific disciplines to ensure that technological products achieve high design efficiency and reflect universal values. Through environmentally conscious and efficiency-oriented approaches, a more sustainable and accessible future can be realized. Simultaneously, developing technologies that maximize performance, conserve time and energy, and minimize environmental impact becomes possible. Meanwhile, nature-based solutions introduce the concept of action within natural and managed ecosystems to address global challenges such as climate change, while benefiting people and supporting the protection and restoration of biodiversity [47]. Ultimately, nature will serve as the foremost guide in shaping environmentally conscious and highly efficient future innovations.

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