Micro/Nano Soft Film Sensors for Intelligent Plant Systems

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Contributor: Qin Jiang , Zhiping Chai , Zisheng Zong , Zhitong Hu , Shuo Zhang , Zhigang Wu

Being abundant as natural intelligence, plants have attracted huge attention from researchers. Soft film sensors present a novel and promising approach to connect plants with artificial devices, helping researchers to investigate plants' intelligence further. For micro/nano soft film sensors that can be used for establishing intelligent plant systems are summarized, including essential materials, fabrications, and application scenarios.

soft film sensors intelligent plant systems plant intelligence

1. Introduction

As an essential part of the ecosystem, plants play irreplaceable roles in the global carbon cycle [1], ecological balance [2], and climate adjustment [3]. In the meantime, plants have inseparable relationships with humankind. In addition to being our primary food source, plants are essential to our daily lives as they offer us industrial resources, purify the air, and heal our emotions. Since most plants lack obviously visible movements, researchers always tend to regard/treat them as passive creatures, lacking effective intelligence and interactions with us. Researchers did not begin to recognize and gradually expose the remarkable intelligence hidden behind plants' inconspicuous behaviors until very recently [4].

The intelligence of plants can be shown in three aspects [5][6]: (1) Basic biological behavior. For instance, plants have developed particular sensory organs that can sense variations in their living environments, such as light intensity, temperature, humidity, and gravity. Based on their biological instincts, plants are able to take superior strategies for adapting to external environments, e.g., tip phototropism [7] and root hydrotropism [8]. (2) Reaction mechanisms. During long-term evolution, plants obtained various inducible defensive or predatory mechanisms for reacting to external stimulations [9][10]. For instance, the *Mimosa pudica* (also known as the shame plant) will close its leaves against insects in response to touch, vibration, and wind. The *Venus Flytrap*, whose traps have miniature antennae, is capable of precisely detecting and facilely catching insects. (3) Swarm intelligence, where a group of species coordinates and cooperate with each other to enhance their individual living ability, has also been widely seen in plants. For instance, certain plant species can distinguish between self and non-self roots to coordinate and compete for absorbing nutrients [11].

Currently, the investigation of plant intelligence is becoming a serious scientific endeavor, yet researchers still have not fully/symmetrically explored it. One of the grandest challenges is to build a connection between plants and human beings' worlds to investigate plants' intrinsic embodiment signals. Soft film sensors, whose active layer thickness features micro/nanoscale structures, show incredible potential in helping researchers to open the door to plant intelligence. Unlike traditional rigid sensors, soft film sensors possess unique flexibility, stretchability, and conformability that allow them to be directly attached to plant surfaces for real-time and individual/collective monitoring [12][13][14]. Most importantly, these sensors cause relatively little disturbance to plants' natural growth or phycological activities. With the help of soft film sensors, the complex biological signals of plants will excite the physiochemical change in active materials, which are then translated into digital ones that are compatible/interchangeable with various modern tools. Ultimately, they can be easily interpreted and widely spread over the world in forms that humans can easily understand. Therefore, combining soft film sensors with plants is one of the most promising ways to establish intelligent plant systems.

Plant physiology detection is one of the most important applications of intelligent plant systems. Soft film sensors can be integrated with plants to investigate plants' biological information to monitor and modulate various vital parameters related to growth, product quality, and living environments. According to these essential physiological data, researchers can establish intelligent plant management systems that supply suitable living environments for plants. Another important application scenario is plant-hybrid systems, where living plants are viewed as biological machines that replace artificial ones. As mentioned above, plants are amazing machines with abundant natural intelligence abilities. Based on soft film sensors, artificial intelligence techniques can be combined with plants to establish intelligent plant-hybrid systems.

Researchers will review soft film-based micro/nano sensors for developing intelligent plant systems (**Figure 1**). To build such a system technically, researchers first overview the essential materials of soft film sensors, including metals, nanomaterials, and polymers. To be compatible with plants, specific materials of soft film sensors need to be selected and modified properly. Then, typical fabrication techniques for soft film sensors are presented, major including laser machining, printing, coating, and vapor deposition. Furthermore, researchers highlight two application scenarios of intelligent plant systems, including plant physiological detections and plant-hybrid systems. Finally, the existing challenges and new opportunities are discussed.

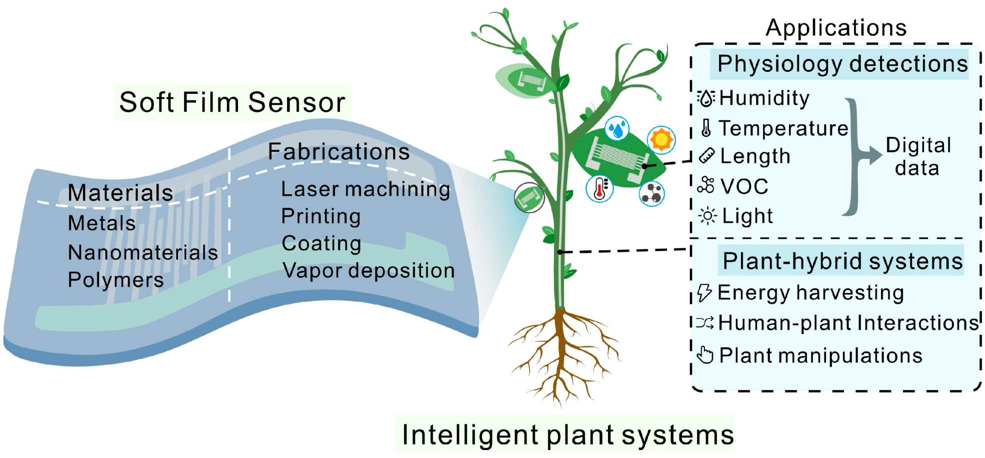

Figure 1. Overview of micro/nano soft film sensor for establishing intelligent plant systems.

2. Materials

Materials are the fundamental factor in micro/nano soft film sensors. As these sensors are attached to tender plant surfaces, soft materials should not only possess low stiffness, flexibility, and stretchability, but also need to consider other specific properties, including biocompatibility, permeability, and conformability. Moreover, modification and synthesis mechanisms are often necessary during material preparation to improve and develop innovative materials with new features and functionalities. Researchers categorize common materials into the following three aspects: metals, nanomaterials, and polymers (**Figure 2**).

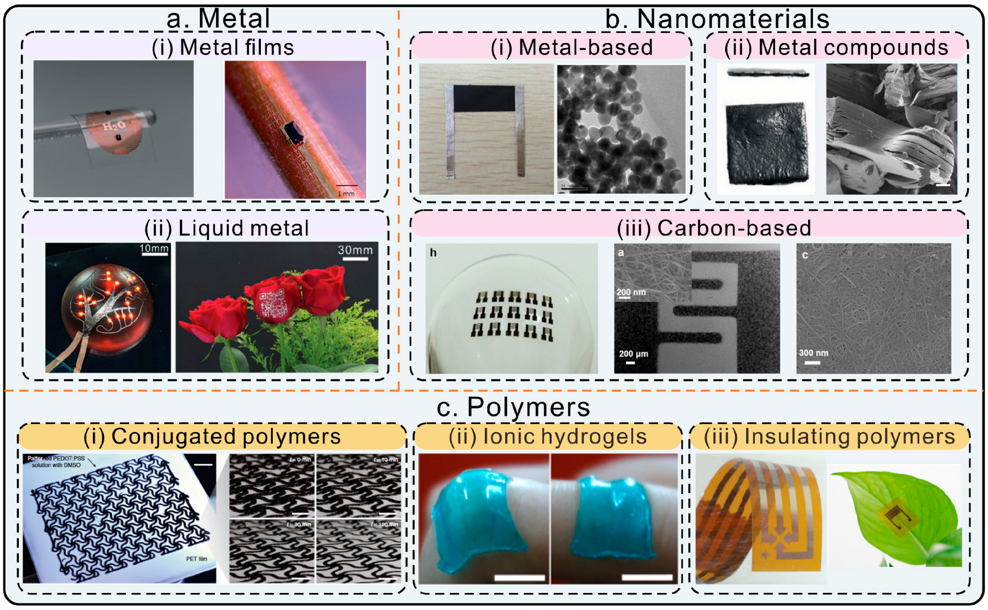

Figure 2. Materials for soft film sensors. (**a**) Metals for fabricating soft film sensors. (i) Metal film-based soft sensors for stem flow detection. (ii) Liquid metal-based soft electronics. Left, liquid metal traces on a hemispheroid. Right, liquid metal patterns on living rose flowers. (**b**) Nanomaterials. (i) Flexible strain sensors with silver nanoparticles as sensing materials. (ii) MXene sheets and SEM images of multilayer MXene particles. (iii) Sprayed CNT interdigital electrodes and SEM images at different magnifications. (**c**) Polymers. (i) Pure PEDOT:PSS hydrogel patterns. (ii) Tough, adhesive, self-healable, and transparent ionically conductive hydrogels as strain sensors. (iii) Polyimide-encapsulated soft film sensors. Left, wearable magnetic field sensors based on polyimide film. Right, soft film sensor attached to the leaf surface.

3. Fabrication

Based on the materials discussed earlier, the technical analysis of their corresponding fabrication techniques is also necessary. Only with proper fabrication processes will these materials function well as a part of sensors. Researchers introduce the fundamental working principle and their applicability. Some specific techniques can directly fabricate soft thin film sensors on fragile plants. Generally, several fabrication processes should be performed consecutively to achieve the final sensors, **Figure 3**.

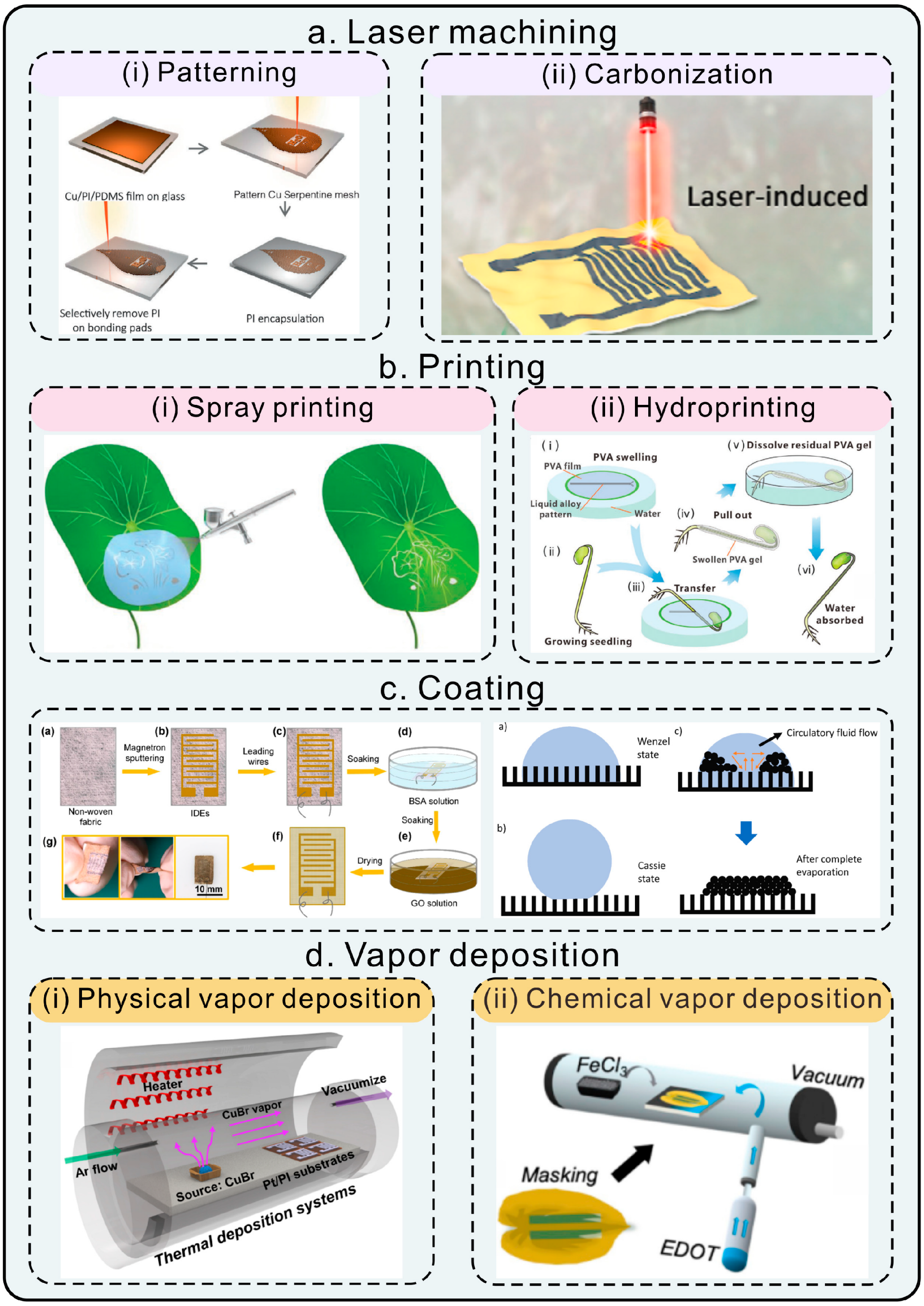

Figure 3. Various fabrication processes of soft film sensors. a) Laser machining. i) Patterning Cu Serpentine mesh. (Reproduced with permission from. ii) Flexible humidity sensor fabricated by laser-induced carbonization. (Reproduced with permission from. b) Printing. i) liquid metal wires on lotus leaf by spray printing. ii) Hydroprinting liquid-alloy-based morphing electronics on living bean sprouts. **c)** Coating. Left, Flexible humidity sensor coated with graphene oxide. Right, a schematic diagram showing the whole process of coating. **d)** Vapor deposition. i) Schematic diagram of CuBr deposited on Pt/PI substrate by high-temperature airflow. ii) PEDOT-based plant sensors fabricated by chemical vapor deposition.

4. Applications

4.1 Physiological detection

Wearable soft film sensors can directly attach to the plant's surface and provide a precise and gentle sensing approach. This technique can detect various on-time data for plant growth and living microclimate. Thus, these soft film sensors can help researchers investigate plant physiology. This technology can be generalized in intelligent and precise agriculture, smart horticulture, botanical research, and so on, see **Figure 4**.

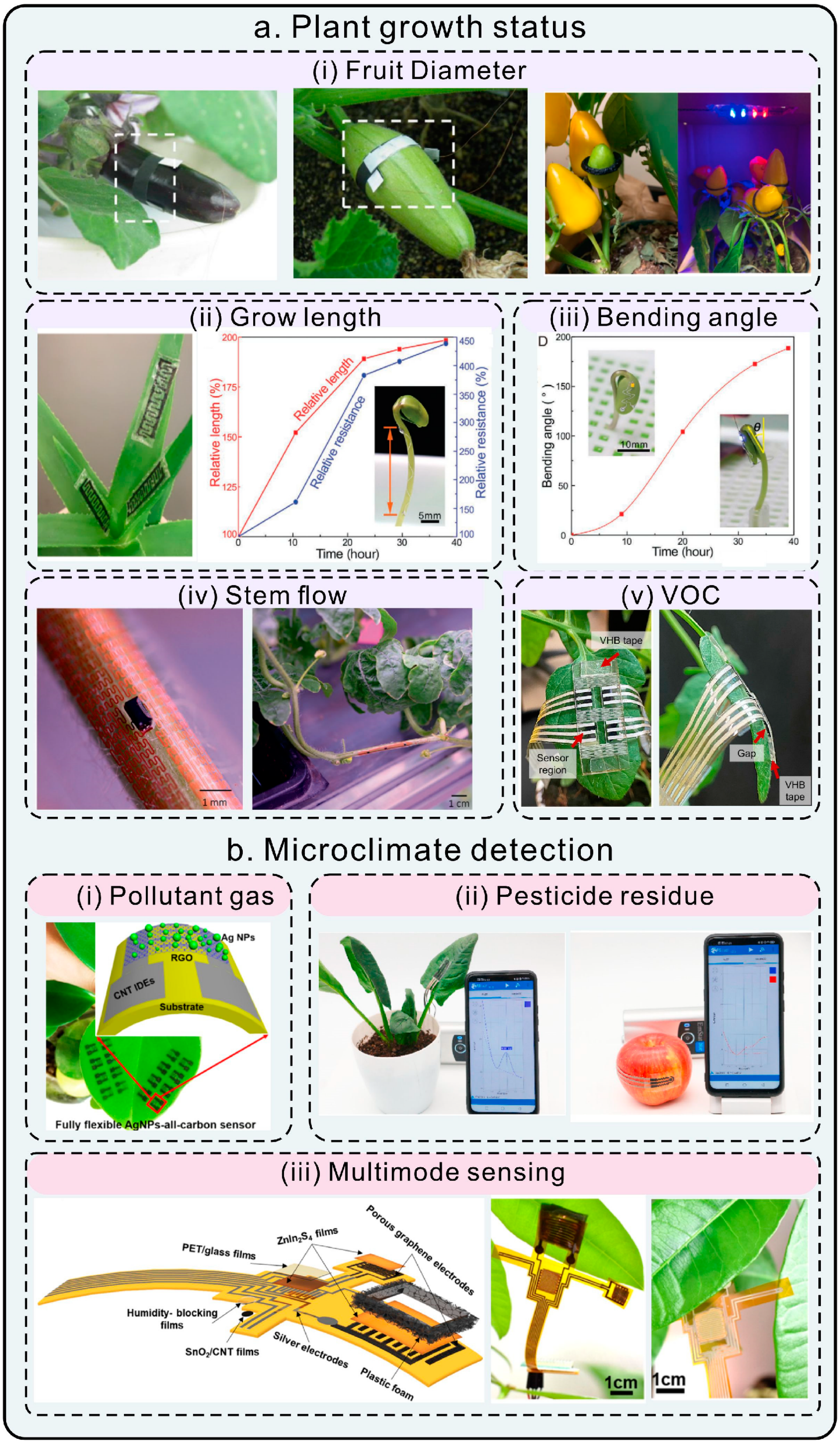

Figure 4. Soft film sensors for plant physiological detection. **a)** Detections of plant growth status. i) Fruit diameter detection. Ii) Grow length detection. iii) Monitoring the sprout's bending angle. iv) Sensors for recording plant stem flow. v) Detection of leaf's releasing VOC. **B)** The detection of microclimate around plants. I) Detection of pollutant

gas surrounding leaves. ii) In situ analysis of pesticide residue of crop surfaces. iii) Multimode sensing for diverse environment parameters, including light, temperature, and humidity.

4.2 Intelligent Plant-hybrid system

In recent years, researchers have been trying to combine soft sensors with plants to generate intelligent plant-hybrid systems. As mentioned above, plants have abundant natural intelligent abilities, yet researchers still have not fully explored them. To cope with this challenge, the soft film sensor acts as a bridge to connect with plants and artificial intelligent systems. Researchers currently conclude intelligent plant-hybrid systems into three aspects: energy harvesting, human-plant interaction, and plant manipulation, **Figure 5**.

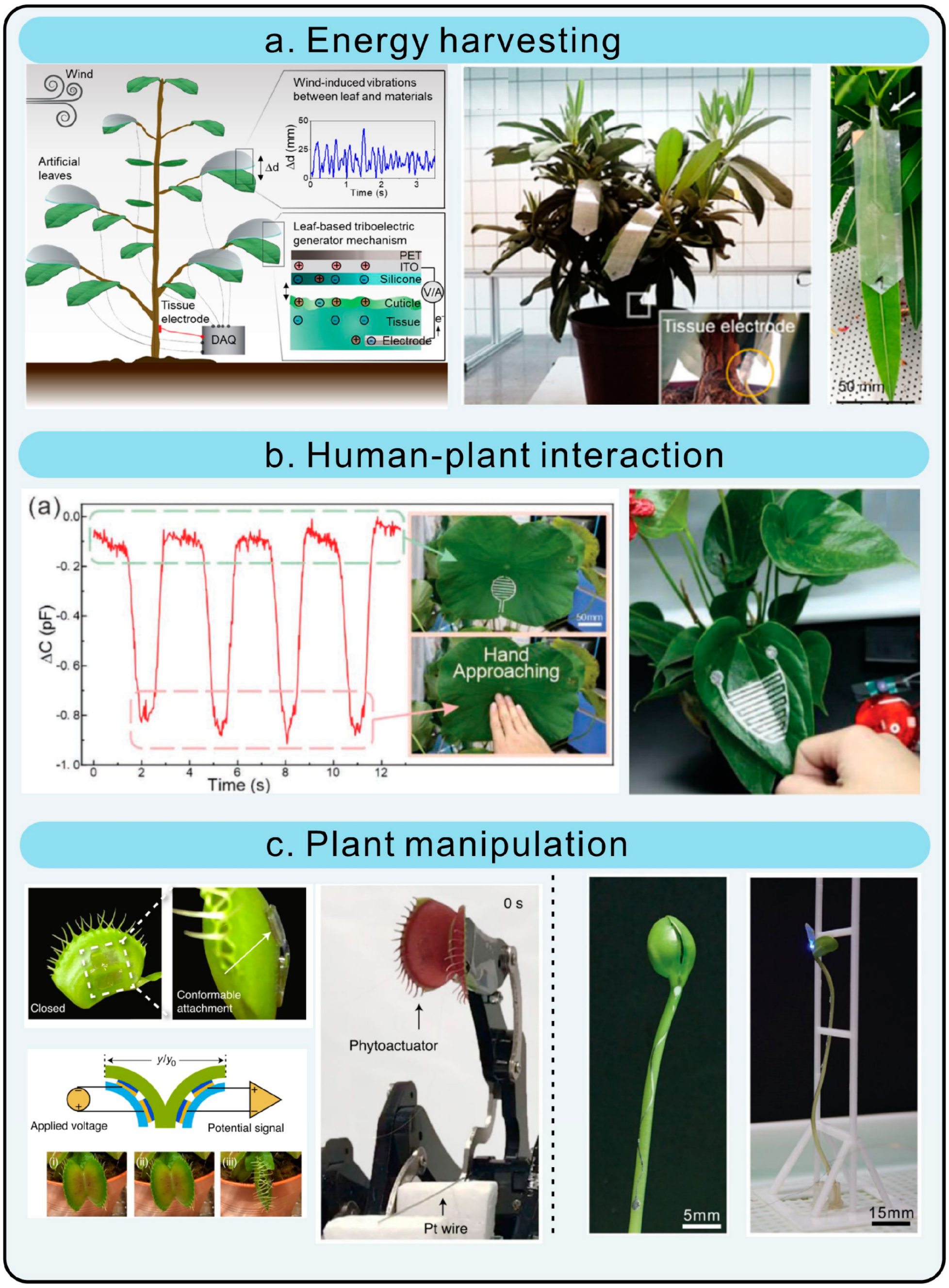

Figure 5. Plant-hybrid systems. **a)** Energy harvesting system that converts wind energy into electricity. **b)** A human-plant interaction system that can sense hand approaching. **c)** Living plant manipulation systems. Left: Manipulating a flytrap to grasp a thin Pt wire. Right: Manipulating a bean sprout to climb a ladder.

5. Conclusions and Perspectives

Plants are amazing biological systems that have abundant natural intelligence. Based on soft film sensors that can be directly attached to plants, various plants' biological information can be precisely transferred to digital signals. Moreover, with the help of soft film sensors, artificial intelligence technology can be closely connected with plants' natural intelligence, forming intelligent plant systems. As mentioned above, soft film sensors have broad applications in monitoring plant physiological information, such as microenvironments, growth status, and crop yield and quality. The information collected from plants can be used as indicators for setting intelligent plant management systems, enabling a new level of precision agriculture, botanical research, and intelligent forestry. Furthermore, plants can be seen as integral machines and combine with soft film sensors to establish intelligent plant-hybrid systems, including energy harvesting, plant-human interactions, and plant manipulations. There are still several grand challenges and opportunities to be explored.

1) Reliable interface matching between soft film sensors and plants. Most existing soft film sensors process soft substrates to adhere to plant surfaces. However, such a bonding strategy can bring a mismatch or detachment caused by plants' rapid and continuous growth. Moreover, tightly attached sensors would hinder plant growth. Therefore, developing a reliable and stable interface between sensors and plants is vital for achieving long time (months and years) wearable detection. LM provides one of the solutions, which can be directly printed on plant surfaces without carrier films. As LM has unique fluidity and ductility, the LM-based sensors can conformally morph with plant growth. Thus, researchers look forward to further developing the next generation of soft film sensors with a stable attachment interface, lower stiffness, and compatibility with plant growth.

2) Multi-sensor fusion. Until now, multimode soft film sensors have been developed to monitor diverse physiological information (such as temperature, light intensity, and water transport). However, these sensors always are placed on a single part of plants (e.g., leaves), where information is very limited. Multi-sensor fusion systems that can be integrated into various plant parts (such as leaves, stems, and roots) may provide more comprehensive and rich physiological information than ever.

3) Higher intelligent plant-hybrid system. In the current stage, plant-hybrid systems have shown the potential for taking full advantage of plant intelligence in different parts, such as energy, interaction, and manipulation. Researchers expect comprehensively integrate these functional parts and thus forming high intelligent plant-hybrid system. The next generation of plant-hybrid systems would possess a high-efficient transforming mechanism, which could harvest various energy from nature (such as wind, rain, light, and temperature). Furthermore, plants can interact intimately with humans, for instance, behaving like "plant pets", where plants can sense human stress and react friendly to comfort humans by releasing pleasant smells.

With the continuous development of essential materials, advanced fabrication technologies, and cross-disciplinary fields, these goals will definitely be achieved soon with the advent of the era of intelligent plant systems.

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