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Review Article

Emerging plant wearable sensors: Materials, manufacturing, multiscale modeling, and applications

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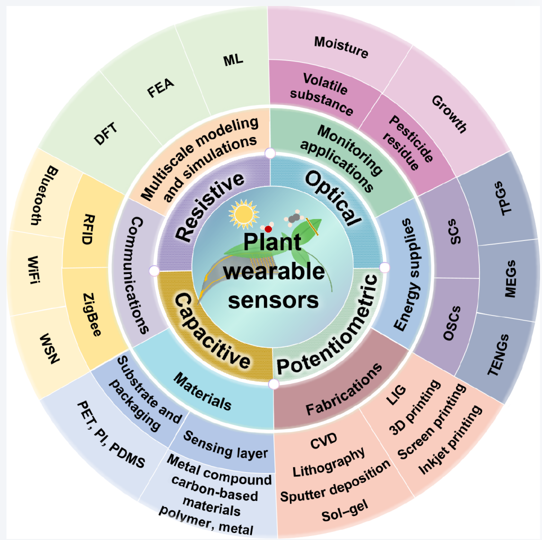
ABSTRACT: Plant wearable sensors (PWSs) can obtain weak plant physiological information under complex agricultural environment in real time and multiple points, offering powerful tools for smart agriculture. However, research on PWSs started relatively late and is strongly interdisciplinary, leaving their development and application still facing challenges. It is therefore necessary to review and trace the evolution of PWSs to clarify their technological trajectory, highlight current progress, and recognize remaining challenges. Herein, PWSs are systematically discussed in terms of their development roadmap, categories, materials, energy-supply technologies, fabrication techniques, and applications. Furthermore, multiscale modeling, such as density functional theory, finite element analysis, and machine learning respectively provides insights from the atomic scale in charge transfer and interfacial interactions, the macro-meso scale in mechanical adaptability and structural reliability, and efficient data analysis, thus advancing the rational design and practical deployment of PWSs. Finally, a systematically curated table, complemented by a comparative radar chart analysis, provides an overview of reported devices by summarizing their key attributes while elucidating strengths and trade-offs for specific applications. This review not only provides guidance for proposing future design strategies and research directions, but also serves as a roadmap for advanced PWSs and facilitating their translation from laboratory research to applications.



KEYWORDS: plant wearable sensors, smart agriculture, manufacturing technologies, flexible electronics, functional materials, multiscale modeling, artificial intelligence (AI)

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1 Introduction

Climate change, including global warming and the frequency of extreme weather events, is placing increasing pressure on agricultural productivity and resource security [1, 2]. Meanwhile, the rising global food demand has led to an increasing reliance on chemical fertilizers and pesticides, which, while boosting short-term yields, also cause soil degradation and water pollution [3]. Plant growth and productivity are shaped by multiple environmental and biological factors, with adverse conditions triggering stress responses [4, 5]. Traditional agriculture relies on manual, single-parameter monitoring, producing delayed data and poor adaptability, making it increasingly insufficient to meet modern food production demands [6]. Therefore, there is an urgent need for advanced, precise monitoring and management tools to ensure sustainable agricultural development.

Smart agriculture integrates advanced technologies to enable intelligent, efficient, and sustainable farming, optimizing resource use and reducing environmental impact [7]. Advances in materials science and information technology have driven the development of diverse sensing systems that collect and analyze real-time crop data, guiding precision interventions, stress-resilient breeding, and improved agricultural resilience [8, 9]. However, rigid sensors are bulky, fragile, and unsuitable for continuous plant contact, often causing interference, physical damage, or measurement errors [10–13]. In contrast, plant wearable sensors (PWSs) with mechanical compliance, stretchability, and biocompatibility overcome these limitations by conforming intimately to plant tissues [14–19], enabling long-term, high-resolution monitoring of water content [12, 16–18], growth [11, 15], hormones [20, 21], volatile organic compounds [22], and pesticide residue [14, 23]. By conforming intimately to plant surfaces, these sensors enable precise, minimally invasive detection that reduces physiological interference while enhancing data fidelity. Recent advances in flexible triboelectric materials make PWSs more feasible. Researchers reuse materials such as waste waterproof textiles as triboelectric layers to achieve self-powered sensing [24, 25]. These systems can collect environmental energy such as wind and rain through liquid–solid or solid–solid contact, while maintaining biocompatibility to plants.

Compared with wearable sensors designed for humans or animals, PWSs are designed to address a fundamentally different set of scientific challenges. These challenges stem from the unique biological realities of plants: They exhibit continuous and irreversible morphological growth, lack protective or self-healing tissues, and are permanently stationed in dynamic, often harsh, outdoor environments. Therefore, the design of PWSs must simultaneously meet three demanding requirements: long-term, growth-adapted mechanical compatibility to accommodate irreversible deformation; minimal interference to basic physiological processes such as photosynthesis, transpiration, and nutrient transport; excellent robustness to environmental variables such as UV radiation, humidity, extreme temperatures, and mechanical disturbances caused by wind and rain. This unique set of constraints points to a different technical path for PWSs.

A typical PWS system comprises sensing units, signal processing circuits, communication modules, energy supply systems, and data analysis platforms. These systems enable continuous acquisition of critical information about plant health and environmental interactions during growth and under stress conditions [26]. Notably, liquid–solid triboelectric nanogenerators (L-S TENGs) have emerged as promising energy solutions for PWSs, efficiently harvesting low-frequency mechanical energy from agricultural environments (such as raindrops and wind-induced leaf vibration) to power low-consumption sensors [27]. For harsh outdoor scenarios, flame-retardant triboelectric materials have also been developed to enhance PWS durability against fire risks while maintaining energy harvesting capability [28], addressing the environmental robustness requirement of agricultural applications.

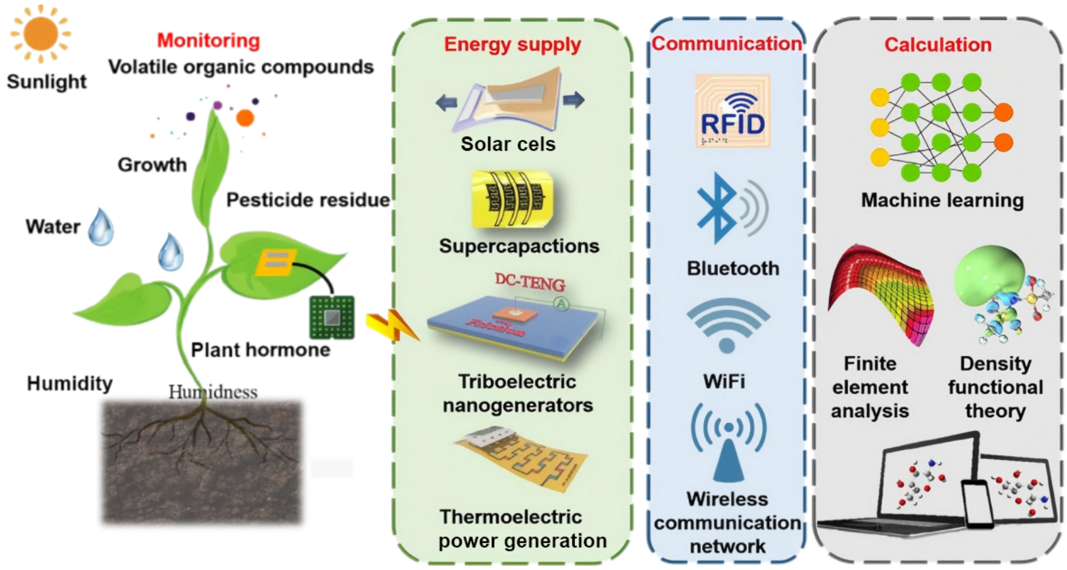
Beyond hardware integration, computational approaches have become core enablers with clear mechanistic links. Density functional theory (DFT) provides atomic-scale insights into the electronic structures, charge transfer, and interfacial interactions of sensing materials, thereby guiding the rational design and optimization of high-performance, stable devices [29]. Finite element analysis (FEA) bridges atomic-scale material design to practical device deployment, simulating PWS macro-mesoscale performance to ensure lab-developed materials translate into plant-compatible, durable sensors. Complementarily, machine learning (ML) algorithms extract patterns from complex datasets, enabling predictive modeling, process optimization, and intelligent decision-making for crop management [30]. The synergistic integration of PWSs with DFT driven materials design, FEA optimized device structures, and ML enabled analytics not only advances fundamental device performance but also transforms agricultural practices by supporting real-time, high-precision feedback to improve productivity, quality, and sustainability [31, 32]. Given the intrinsic complexity of plant systems and the diverse performance requirements of PWSs, single-scale design strategies are insufficient to address challenges spanning materials, device mechanics, and system integration. Multiscale modeling therefore emerges as a critical enabling framework, linking atomic-level material behavior, device-level mechanical reliability, and system-level data interpretation. This review highlights multiscale modeling not as an isolated topic, but as a unifying thread that supports material selection, fabrication optimization, and application-oriented sensor design.

This review provides a comprehensive overview of PWSs, emphasizing their fundamental architectures, constituent materials, fabrication techniques, and diverse applications in smart agriculture (Scheme 1), thereby laying a theoretical foundation for intelligent agriculture and precise interventions. We summarize advances in materials, fabrication, and device architectures, establishing a framework that links material properties, manufacturing processes, and application scenarios to accelerate high-performance PWS development. DFT is emphasized for guiding molecular-level sensor design, FEA highlighted as a key tool for optimizing fabrication outcomes, while ML enables interpretation of complex signals, stress prediction, and data-driven decision-making. Furthermore, the strengths and trade-offs of each sensor type are elucidated through a comparative radar chart analysis, providing a unique perspective on their suitability for specific applications, while a systematically curated table serves as a quick-reference guide to the diverse landscape of reported devices, comparing their key attributes, materials, and performance metrics. This work provides strategic guidance for reliable, scalable, and sustainable PWS applications in smart agriculture.

2 Plant wearable sensing systems

2.1 Development roadmap of PWSs

The concept of PWSs originates from early human and animal wearable devices. With the advancement of flexible electronics, bioelectronics and sensor technologies, the concept was gradually expanded to plants. Initially, the development path of PWSs was similar to that of human wearable devices, and then innovations in materials, manufacturing processes and sensing principles led to truly plant-specific sensing technologies. Several important



Scheme 1 System architecture of plant wearable sensors.

milestones in its evolution can be seen shown in Fig. 1(a). Smart agriculture emerged in the 1980s but was limited by technological bottlenecks such as low-precision sensor systems, underdeveloped data transmission networks, and lack of efficient data analysis tools. In the 2000s, key breakthroughs were made in basic research in the field of flexible and stretchable electronics. Representative results include the pioneering work of Rogers' team on "electronic skin" [33] and the cutting-edge research on flexible semiconductors and conductive polymers (e.g., CNTs and poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS)) by Bao's team [34, 35]. These advances have laid the technological foundation for integrating high-performance electronics on flexible substrates, thus breaking through the material and structural bottlenecks that previously constrained the development of flexible electronics [36, 37]. While early flexible electronics primarily pursued human-centric metrics like skin-comfortable stretchability and high-fidelity biopotential recording, the development of PWSs has been driven by the imperative for plant-specific functionalities. These include true biocompatibility that avoids hindering growth, mechanical designs that adapt to, rather than resist, plant expansion, and environmental resilience for sustained outdoor operation. It is these plant-imposed challenges that motivate and shape the specialized sensing mechanisms, novel materials, and unique system architectures explored throughout this review, clearly distinguishing PWSs as a dedicated field of research.

Between 2010 and 2015, the rapid spread of the Internet of Things (IoT), cloud computing, and radio-frequency identification (RFID) technologies facilitated the transition of sensors from independent devices to interconnected nodes, thereby establishing the groundwork for digital and networked plant monitoring. Subsequently, from 2016 to 2019, flexible sensors began to gain practical application in plant systems; meanwhile, the incorporation of big data analytics further enhanced their effectiveness. These advances have significantly enhanced the important role of PWSs in promoting the development of smart agriculture [38, 39]. Notably, this period witnessed a shift from single-parameter sensing to multi-parameter integration, but limitations in data transmission distance and energy supply durability remained, which consequently constrained large-scale field deployment.

The period from 2020 to 2025 witnessed rapid technological breakthroughs, including advances in flexible moisture-enabled electricity generation (MEG), thermoelectric power generation (TPG), and TENG technologies. Such technological breakthroughs have successfully resolved the persistent issue of sustained power supply [40–42]. Meanwhile, the integration of low-power wireless communication technologies including bluetooth, Wi-Fi, and 4G/5G broke through the constraints of wired connections and short-distance data transfer, facilitating remote, real-time monitoring in large-area agricultural plots [43, 44].

Looking ahead, with the rapid development of artificial intelligence (AI) technology, combining it with PWSs can allow for deep mining and analysis of collected large-scale, multidimensional data. This process can extract the valuable information implicit in the data, thus providing different crops with refined planting guidance that matches their growth needs, and ultimately significantly improving crop yield and quality [45, 46]. This evolution also signifies that agriculture is shifting from the traditional model of relying on experience to a new stage of data-driven smart agriculture [47]. The exponential growth in publications in recent years underscores the rapid progress of emerging PWSs (Fig. 1(b)), driven by breakthroughs in advanced materials, self-power energy, communication networks, and AI.

2.2 Categories of PWSs

In recent years, PWSs have emerged as prominent tools for real-time monitoring of plant physiological and environmental signals. Currently, the common sensing mechanisms mainly include resistive, capacitive, potentiometric, and optical types. Among them, resistive, capacitive, and potentiometric sensors have been more applied in practice due to their easy integration with flexible electronic devices. However, their widespread adoption is often accompanied by trade-offs between sensitivity, selectivity, and long-term stability under fluctuating agricultural environments. Meanwhile, optical sensing technology is gaining growing attention due to its high sensitivity and strong potential for biochemical detection [48, 49], although its practical deployment is still constrained by system complexity and cost. These different technological paths have their own advantages and complement

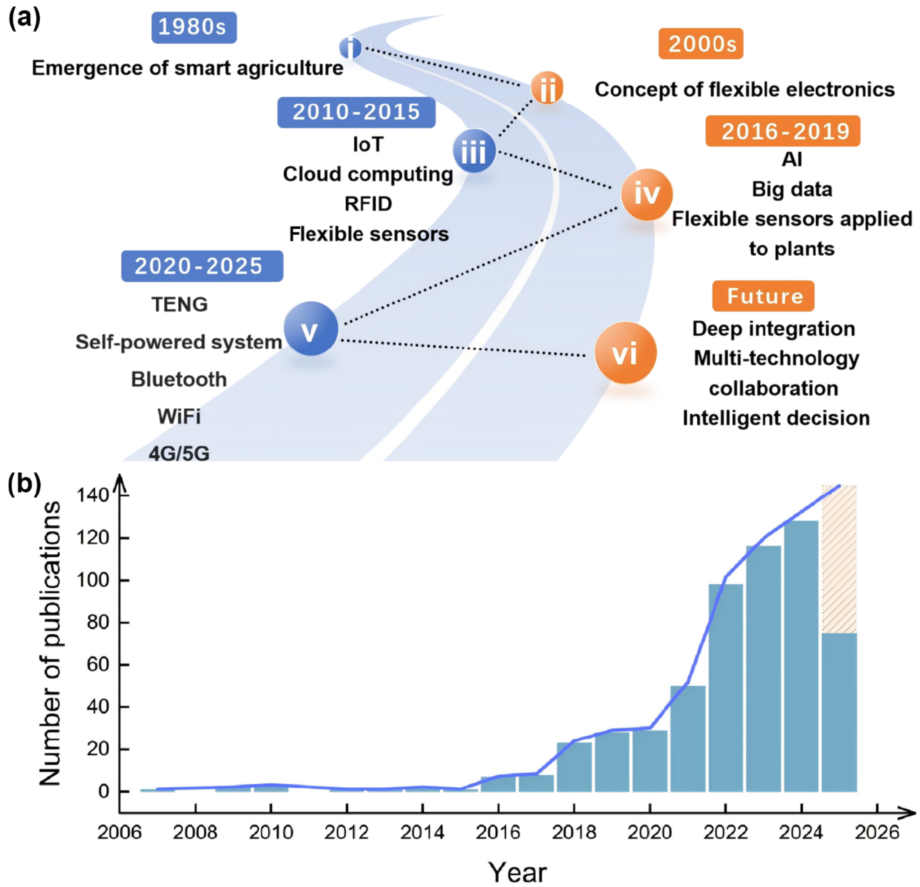


Figure 1 Development roadmap of PWSs. (a) Timeline of smart agriculture and PWSs. (b) Annual publications related to PWSs in recent years, retrieved using "plant wearable sensors" as a keyword in Web of Science, with data updated to September 2025; the shaded portion indicates the projected number of publications for the remainder of 2025.

each other, thus forming the technical foundation for the development of PWSs.

2.2.1 Potentiometric type

Potentiometric PWSs mainly rely on detecting changes in electrical potential in response to stimuli such as ions, chemical signals or biomolecules in the external environment [50, 51]. Ion-selective electrodes facilitate quantitative determination of specific ions, offering information about plant nutrient status or ionic variations associated with stress responses [52, 53]. Potentiometric biosensors incorporate biomolecular recognition elements, such as enzymes, antibodies, or DNA to achieve selective detection of target biomolecules through potential changes. From a comparative perspective, potentiometric sensors offer high chemical selectivity and low power consumption; however, their signal stability can be affected by ion interference, biofouling, and drift during long-term plant attachment. Mechanistically, these limitations originate from the sensitivity of interfacial potentials to local chemical fluctuations at the electrode-plant interface. This combination of electrochemical responsiveness and molecular selectivity enables potentiometric sensors to monitor physiological and biochemical processes in real time, providing valuable information for precise plant monitoring and intelligent agriculture applications.

In addition, the operation of PWSs based on the friction electric principle relies on the process of charge transfer and accumulation that occurs when two different materials come into contact and separate, resulting in the formation of a voltage difference (Fig. 2(a)). This voltage difference drives an external circuit to generate current for energy conversion and signal detection [54, 55]. Specifically, when two materials are in contact, electrons are transferred from one material to the other, causing opposite charges to their surfaces. These charges are temporarily retained due to electrostatic forces, and upon separation, a current or voltage signal is generated. Subsequently, the electrode layer collects and conducts these charges, converting them into detectable electrical signals. This type of sensor has found broad application in both energy harvesting and plant/environmental monitoring.

2.2.2 Capacitive type

Capacitive PWSs mainly sense the physiological state of plants or environmental changes by monitoring changes in capacitance values. Such capacitance changes often originate from changes in the dielectric properties of the sensor material or the adjustment of the distance between its internal electrodes [17, 56]. Changes in plant water content, tissue deformation due to growth or mechanical stress, and local ionic concentrations can all modulate capacitance. These variations are converted into electrical signals through measurement circuits, enabling real-time, non-invasive monitoring of plant hydration, mechanical status, and biochemical cues. Graphene oxide (GO) has been employed as a hygrosensitive material for fabricating flexible capacitive sensors that can be directly attached to plant leaves (Fig. 2(b)), enabling real-time tracking of transpiration through stomatal activity without causing damage to the plant [17]. Such capacitive sensors therefore offer a

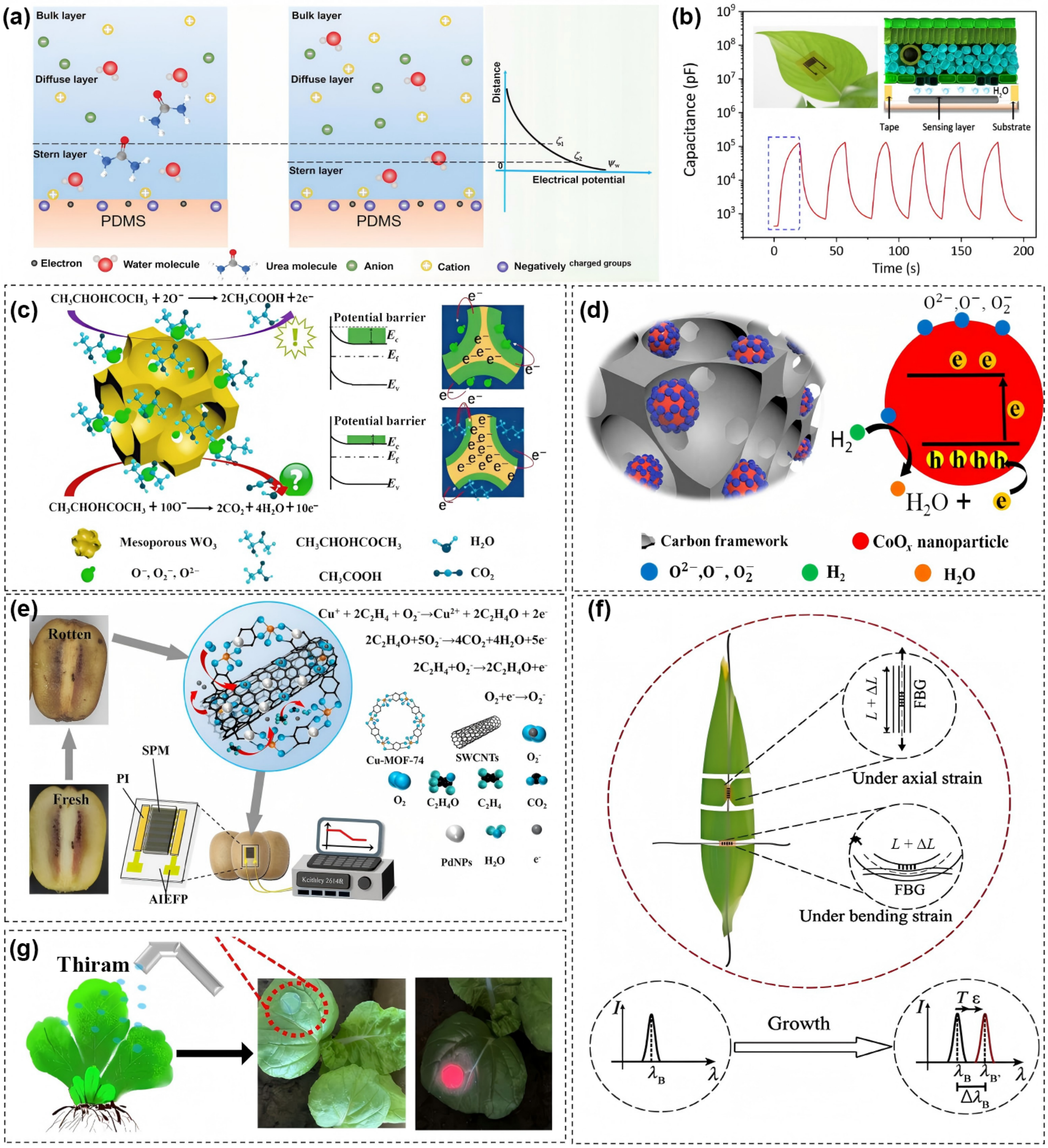


Figure 2 Categories of PWSs based on sensing mechanism. (a) Potentiometric type PWS based on the operation of TENG. Reproduced with permission from Ref. [54], © Gao, A. L. et al. 2024. (b) Capacitive PWSs for drought monitoring. Reproduced with permission from Ref. [17], © Elsevier B.V. 2020. (c) N-type resistance type. Reproduced with permission from Ref. [60], © American Chemical Society 2017. (d) P-type resistance type. Reproduced with permission from Ref. [61], © American Chemical Society 2016. (e) Chemical resistance type. Reproduced with permission from Ref. [63], © Elsevier B.V. 2024. (f) Optical type sensor of FBG located on the surface of the corn. Reproduced with permission from Ref. [64], © Elsevier B.V. 2024. (g) Monitoring the degradation of pesticides using the fluorescence method. Reproduced with permission from Ref. [66], © Wiley-VCH GmbH 2025.

promising approach for continuous, high-resolution monitoring of plant physiological states in precision agriculture. However, capacitive PWSs are intrinsically sensitive to ambient humidity and parasitic capacitance, which may cause signal drift under field conditions. Common mitigation strategies include hydrophobic/porous dielectric design, encapsulation layers, differential measurement structures, and multi-parameter compensation.

2.2.3 Resistive type

Resistive PWSs utilize conductive or semiconductive materials, where changes in environmental conditions affect the resistance of the material, such changes can be detected by measuring variations in resistance [18, 57, 58]. Resistance mechanisms are generally categorized into two types. One type involves semiconductor metal oxide resistive sensors, which typically require high operating temperatures and exhibit poor moisture resistance, therefore, they are commonly classified as gas-sensitive resistive sensors. For instance, the interaction between an n-type metal oxide semiconductor (MOS) sensor and a target gas can be explained by the surface depletion model. In this model, oxygen adsorption on the sensor's surface reduces the number of free charge carriers, thereby increasing resistance through the formation of a space charge layer. Conversely, when exposed to a reducing gas, the target molecule reacts with the oxygen anions, releasing electrons and decreasing the resistance [59].

The sensing mechanism under the MOS structure can be further illustrated by the following two specific examples. For an n-type WO_3 MOS sensor (Fig. 2(c)), when it is in air, oxygen molecules adsorb on the surface of the material, trapping free electrons in the semiconductor to form negatively charged oxygen ions (O_2^-, O^-, O^{2-}). This process creates a space charge layer near the surface, resulting in an elevated energy barrier and a subsequent increase in resistance. In contrast, when the sensor is exposed to a reducing gas, the gas molecules react with the oxygen ions on the surface, releasing the electrons back into the semiconductor, thus lowering the resistance [60]. In p-type CoO_x nanoparticles (Fig. 2(d)), oxygen molecules first capture electrons from the conduction band of the CoO_x/C composite and react to form O_2^-, O^-, and O^{2-} species on the surface. This adsorption process creates holes, thereby increasing the material's resistance. When the sensing material is subsequently exposed to an H_2-air mixture, the reducing H_2 molecules react with the oxygen anions to produce H_2O molecules [61]. This reaction returns electrons to the CoO_x, filling some of the holes and leading to a rapid increase in resistance. In addition, there is a class of resistive sensors that can operate at room temperature and they rely on a thin film of sensitive material. When this film comes into contact with the target detector, an electron transfer occurs as a result of the physical or chemical interaction between the two, thus changing the conductivity of the material [62]. As an illustration, a resistive ethylene gas sensor constructed using SWCNTs/PdNPs/Cu-MOF-74 nanocomposites was fabricated [63]. This sensor operates via oxygen adsorption, with PdNPs catalyzing the cleavage of ethylene bonds and Cu-MOF-74 providing molecular selectivity for ethylene detection (Fig. 2(e)). The principle of current-based sensors is similar with resistive sensors, which reflect detection results by measuring the current flowing through the sensor [14, 23]. Although the resistive PWS has the advantages of high sensitivity and fast response, its long-term stability and selectivity are still significantly insufficient. Especially in the agricultural environment where temperature and humidity fluctuate violently, these problems are more prominent. In principle, this is mainly due to the fact that the surface adsorption–desorption process and conductive path are easily disturbed by the environment.

2.2.4 *Optical type*

Optical sensing mechanisms have become a critical area in the development of PWSs. These sensors monitor key physiological indicators of plants by capturing changes in light signals, such as wavelength shift, intensity modulation, reflectance, fluorescence, or colorimetric transitions. In comparison with electrochemical approaches, optical PWSs offer high sensitivity and immunity to electromagnetic interference; however, their reliance on external light sources increases system complexity and limits large-scale field deployment. Among them, fiber-optic-based sensors have received particular attention, especially the fiber Bragg grating (FBG) sensor. It has a periodic structure etched inside the fiber that reflects light of a specific wavelength. When the external environment changes in strain, temperature or humidity, the wavelength of the reflected light will be shifted accordingly, and by detecting this shift, non-contact measurement of the relevant state of the plant can be realized. When the optical fiber undergoes twisting or deformation, the reflected wavelength shifts accordingly, and this principle can be used to quantify plant growth behavior, such as tracking elongation patterns in corn (Fig. 2(f)). These findings demonstrate that optical fiber sensors provide a promising route for long-term, non-destructive, and highly sensitive monitoring of plant developmental processes [64]. Their immunity to electromagnetic interference, multiplexing capability, and flexibility make them well-suited for continuous monitoring of plant bending, growth strain, and water status.

Beyond fiber optics, various other optical approaches have been employed to enhance the performance and applicability of PWSs. Colorimetric sensors respond to environmental stimuli (such as pH or volatile organic compounds) by undergoing visible color changes, enabling simple visual inspection [65]. Fluorescence-based PWSs employ fluorophores that change their emission behavior in response to specific biochemical stimuli. For example, a plant wearable fluorescent sensor using hydrogel material can fit tightly on the crop surface and can achieve rapid and accurate quantitative detection of triazinone pesticides within two minutes (Fig. 2(g)). The device not only assesses pesticide residues, but also tracks the dynamic decomposition process of pesticides on the plant in real time without damaging the crop [66].

In addition, spectral reflectance sensors assess chlorophyll content, water stress status, or the presence of diseases by analyzing changes in reflectance of leaves or fruits, and such technologies are often combined with imaging systems for large-scale crop phenotyping [67]. Meanwhile, surface plasmon resonance sensors rely on changes in the resonance state of the metal-dielectric interface to detect molecular binding events, showing excellent selectivity and application potential for real-time biochemical monitoring in plants [68]. Together, these features demonstrate the unique value of optical PWSs in enabling highly sensitive, selective, and sustainable monitoring of plant-agrochemical interactions.

Selectivity, long-term stability, and environmental interference are still common bottlenecks faced by various sensing technologies, but the physical and chemical root causes of these problems vary according to different working principles. Therefore, most of the existing solutions are only for specific sensing mechanisms, and often need to strike a balance between different performances, and it is difficult to completely solve all problems. This also prompts us to choose sensors according to specific needs in practical applications, and actively adopt the design idea of hybrid sensing. At the same time, these sensing challenges are also driving the development of multiscale modeling methods that provide theoretical guidance for the optimization of specific mechanisms by simulating the interactions between materials and signals.

2.3 Energy supply

With the continuous development of plant wearable electronic devices, agricultural practices are gradually moving from traditional models to modernization, standardization, and intelligence. However, the problem of energy supply for a large number of sensors and microdevices is still one of the key challenges hindering the large-scale application of smart agricultural technologies [69].

Unlike controlled laboratory environments, agricultural fields impose long-term, low-maintenance, and environmentally adaptive energy demands, making conventional batteries insufficient for sustained deployment. Conventional power supply methods are difficult to meet the long-term, low-cost, high-flexibility, and low-environmental-impact energy needs of field sensors, which are susceptible to external conditions, have a limited lifespan, and require frequent maintenance. These limitations also constrain electronic devices from moving further towards miniaturization and portability [70]. As a result, there is an increasing industry demand for power solutions that can operate stably in complex outdoor environments. Emerging technologies such as flexible solar cells, supercapacitors, and nanogenerators are becoming important supports for realizing self-powered systems for PWSs.

2.3.1 *Organic solar cells*

The development of organic solar cells (OSCs) has advanced in three sequential phases: rigid, flexible, and stretchable configurations (Fig. 3(a)). Among these, rigid OSCs, though achieving certain breakthroughs in power conversion efficiency, are fabricated on glass substrates and have poor mechanical properties, failing to meet the flexibility requirements of wearable electronics. Subsequently developed flexible OSCs turn to plastic substrates, which are able to adapt to a certain degree of bending, but are still difficult to fully adapt to the diverse mechanical stresses in real use environments due to their limited horizontal strain capacity and susceptibility to damage in the face of tensile or complex deformation.

The further developed stretchable OSC is able to adapt to more complex mechanical environments, and maintains its structural stability and reliable performance, whether it is bent vertically or stretched horizontally. Even under higher strain conditions, it is less prone to significant film deformation or performance degradation [71]. Semi-transparent solid-state solar cells with rubber-like elasticity have been successfully prepared, which can be repeatedly stretched and deformed at room temperature and still maintain high power conversion efficiency and stable electrical performance [72]. The key mechanism enabling stretchability is the introduction

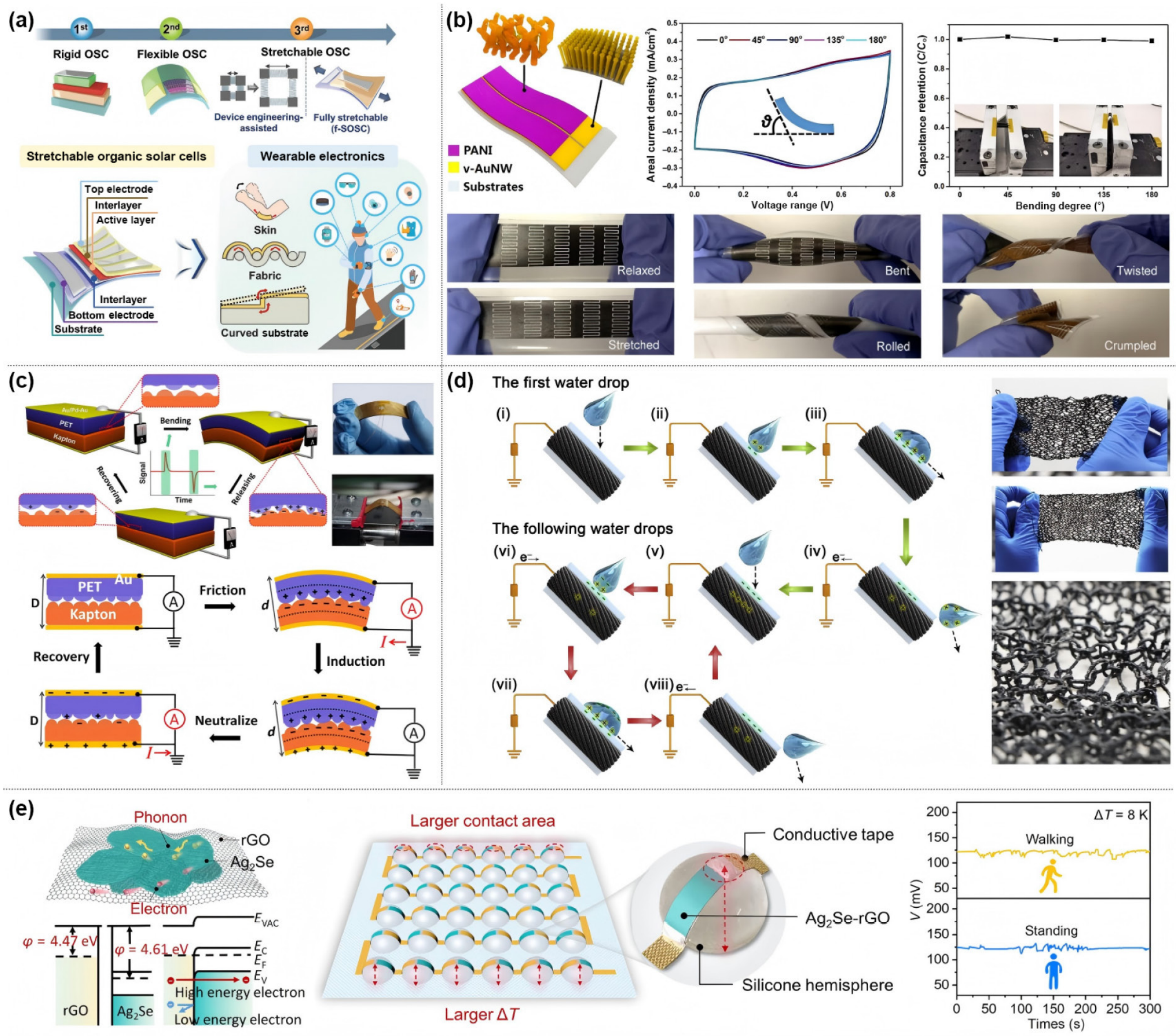


Figure 3 Different energy supply strategies. (a) Development and applications of OSCs. Reproduced with permission from Ref. [71], © Wiley-VCH GmbH 2022. (b) Different bending capabilities and stability of supercapacitors. Reproduced with permission from Ref. [73], © WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim 2018. Reproduced with permission from Ref. [74], © Park, S. et al. 2018. (c) Structure and principle of TENG. Reproduced with permission from Ref. [40], © Elsevier Ltd. 2012. (d) Yarn-like TENG collects the energy from raindrops. Reproduced with permission from Ref. [78], © Elsevier Ltd. 2020. (e) TEG transfer mechanism based on Ag_2Se-rGO films. Reproduced with permission from Ref. [83], © Zhang, L. et al. 2025.

of elastic polymer matrices (such as polydimethylsiloxane (PDMS)) and wrinkled film structures, which disperse mechanical stress during deformation. However, semi-transparency sacrifices small portion of power conversion efficiency compared with opaque OSCs. This special structural design enables it to fit skin, fabrics, and various types of curved surfaces, demonstrating excellent surface adaptability and fitting ability. Therefore, they show great potential in wearable electronics and are expected to become ideal power sources for self-powered wearable devices. Compared with rigid and flexible OSCs, stretchable OSCs exhibit superior mechanical adaptability to plant growth and leaf deformation. However, this advantage often comes at the expense of reduced power conversion efficiency and long-term outdoor stability, particularly under prolonged UV exposure and humidity fluctuations.

2.3.2 Supercapacitors

Although supercapacitors typically have a lower energy density than batteries, they have a higher power density, making them more suitable for high-power scenarios that require rapid charging and discharging. In addition, stretchable supercapacitors maintain stable charging and discharging performance when subjected to large mechanical deformations, making them an important option in the field of flexible energy storage. For example, researchers prepared a skin-like electrochemical supercapacitor by self-assembling vertically aligned gold nanowires and combining them with the electrodeposition of polyaniline (PANI) [73]. The capacitor is very flexible and does not affect its electrical performance regardless of the angle from which it is bent (upper part of Fig. 3(b)).

Similarly, a stretchable micro-supercapacitor was successfully constructed using a heterostructure formed by reduced graphene oxide (rGO) and gold [74], which forms a stable three-dimensional (3D) network capable of retaining high conductivity under various stress conditions including relaxed, bent, twisted, stretched, rolled, and crumpled states, as illustrated in the lower part of Fig. 3(b). The energy storage mechanism of these supercapacitors is based on electric double-layer capacitance (rGO/gold) and pseudocapacitance (PANI), with the 3D network structure ensuring both mechanical stability and ion transport efficiency. These characteristics indicate that stretchable supercapacitors, with their mechanical robustness and compatibility with deformable substrates, can function as dependable energy-storage modules for plant-wearable devices. Their ability to adapt to shape changes induced by plant growth helps address one of the key challenges faced by longterm field-deployed PWSs, namely the need for a resilient and consistent power supply. Despite their excellent power density and mechanical robustness, supercapacitors alone are insufficient to support long-term autonomous operation of PWSs, necessitating their integration with energy harvesting units.

2.3.3 Triboelectric nanogenerators

Agricultural environments provide abundant sources of renewable energy, including low-frequency, random, and irregular inputs such as wind, rain, and water flow. TENGs harvest mechanical energy from the environment to drive charge transfer within the material, thereby generating an electric current [69]. A schematic illustration of their structure and working principle is shown in Fig. 3(c), charges are generated by rubbing two polymer films, which results in the creation of a triboelectric potential layer at the interfacial region (indicated by dashed lines), a mechanical compression results in a change in the distance between the two electrodes (from D to d), thus, under the driving of the triboelectric potential, a change in system capacitance leads to the flow of current in the external load which drives the flow of the free electrons across the electrodes to minimize the total energy of the system [40, 75]. In contrast to solar-based strategies, TENGs are particularly effective for harvesting low-frequency and intermittent mechanical energy; however, their output power density is highly dependent on environmental dynamics and device configuration.

To effectively harvest these energy sources, the design of TENGs requires the selection of appropriate materials and surface modification methods tailored to specific application scenarios. TENGs designed for harvesting raindrop energy typically require a superhydrophobic surface to achieve high conversion efficiency [70]. When mounted on plant leaves, TENGs need to be lightweight, breathable, and stretchable so as not to disrupt photosynthesis and other physiological processes [44, 76, 77]. In agricultural environments, wind-induced blade vibration is an often-overlooked source of energy. To effectively harvest this low-frequency vibration energy, Jiang's research team designed a flexible single-electrode friction nanogenerator based on a PDMS film with laser-induced graphene (LIG). The device attaches to the leaf, with PDMS serving as the negative triboelectric layer and the leaf blade as the positive layer. When the PDMS film oscillates with the wind and is in periodic contact with other blades, it is able to convert wind energy into electrical energy and realize efficient capture of environmental energy [41]. A critical analysis of this design reveals that the use of LIG enhances conductivity and mechanical stability. However, the single-electrode structure yields lower power output than dual-electrode TENGs, a fundamental trade-off between device simplicity and energy harvesting efficiency.

Given the abundance of plants in agricultural settings, combining TENGs with plants for raindrop energy harvesting is feasible. A stretchable triboelectric yarn (ca. 400 μm in diameter) has been developed to convert raindrop energy into electricity (Fig. 3(d)). The yarn can protect crops while powering equipment, which can have a positive effect on improving crop yield and quality. This friction electric yarn produces a voltage output of 7.7 volts and exhibits good mechanical properties, including high stretch, structural stability, and strong hydrophobicity [78]. Although this type of design demonstrates the potential of integrating friction electrical components with plants, solutions that utilize fully degradable materials offer additional advantages. For example, a fully biodegradable friction nanogenerator is made of natural materials in which the leaf skin forms part of the friction electrical system together with internal conductive elements [79]. This device is able to efficiently harvest the energy generated when raindrops strike the blade, and the hydrophobic structure of its surface, similar to a lotus leaf, helps the droplets to roll off and thus work continuously. In addition to having excellent mechanical properties, it can fit irregular plant surfaces and shows good biocompatibility.

To enhance the efficiency of environmental energy harvesting, researchers developed a friction nanogenerator with both waterproof and breathable properties by weaving polyvinylidene fluoride-hexafluoropropylene nanofibers into fluorocarbon nanotube microspheres. The device is able to simultaneously convert wind and raindrop energy into electricity, thus providing continuous power for wireless PWSs and realizing real-time monitoring of plant health [80]. The TENG demonstrates mechanical compliance, strong electrostatic adhesion, and holds great potential for establishing self-powered agricultural systems. In terms of the underlying mechanism, this variability originates from the stochastic nature of contact-separation events and charge transfer efficiency at the triboelectric interface.

2.3.4 Other power generation

The principle of TPG is based on the Seebeck effect, which states that when two different conductors or semiconductor materials form a closed loop and a temperature difference exists between the two ends, an electromotive force is generated in the loop, thereby producing an electric current and enabling the direct conversion of thermal energy to electrical energy [81].

In the field of flexible wearables, this principle has been innovatively applied. For example, Chen's team developed an ultra-thin, flexible thermoelectric film based on bismuth telluride [82] by employing "nano-adhesive" Te nanorods and spark plasma sintering technology. After 1000 bending tests, the material exhibited only a 5% performance loss, and it can generate electricity by utilizing the temperature difference between the human body and the environment, offering the potential to replace batteries in powering wearable devices. The same group prepared a flexible Ag_2Se/rGO composite film by utilizing chemical solution processing and related technologies (Fig. 3(e)) [83]. The rGO network in the Ag_2Se/rGO composite promotes efficient electron transport, while the strong Ag_2Se/rGO interface enhances phonon scattering, achieving decoupling between electrical conductivity and the Seebeck coefficient. Based on this design, a 14 cm × 14 cm flexible thermoelectric generator with 100 thermoelectric leg pairs was fabricated, capable of conformal contact with curved surfaces. On-body tests showed a stable output of ~ 120 mV for 300 s under both static and walking states, demonstrating its reliability for body-heat harvesting and powering wearable electronics.

In addition to TPG, MEG is an emerging technology that directly converts air humidity into electricity through interactions between nanostructured materials and water molecules. Researchers developed a nanoporous hydrogel using a pomelo peel framework with *in situ* crosslinking of citric acid and carboxymethyl cellulose [84]. MEG technology operates based on three closely related links: moisture adsorption in nanopores, subsequent ion dissociation, and gradient-driven ion migration. By regulating the size, density and surface characteristics of nanopores in a targeted manner, researchers can optimize each of the above steps separately, thereby effectively improving the overall power generation performance. The uniform, high-charge-density nanopores enhance water absorption, ion dissociation, and directional ion transport, leading to significantly improved output potential. Their work demonstrates the feasibility of boosting MEG performance through nanopore engineering in organic hydrogels and provides a promising materials design strategy for sustainable energy and environmental remediation. TPG and WEG provide feasible energy supply solutions for battery-free PWS in specific environments. However, their actual power generation performance is largely dependent on temperature or humidity gradients present in the environment, which are often limited and unstable in open farmland, making it difficult to achieve a sustained, reliable energy supply.

2.4 Wireless communication technologies

In fact, within the PWS platform, data transmission acts as a critical "mediator" that bridges PWS sensors with the data processing terminals. PWSs initially transform plant physiological or growth-related changes into electrical outputs. These signals must then be transmitted to external devices such as smartphones, tablets or RFID readers [85]. The reliability and scalability of wireless communication therefore directly determine whether PWSs can transition from laboratory demonstrations to field-deployable systems. Only after transmission can the data be preprocessed, translated into quantitative indicators and used for detailed assessments of plant health [86, 87].

Signal transmission in current systems mainly follows two routes: wired and wireless. A representative wired platform integrates laser-etched graphene electrodes with a handheld smartphone detector, using conductive silver ribbons for connection. While wired transmission offers high signal fidelity and low latency, it inevitably restricts device mobility and plant growth adaptability, making it unsuitable for long-term field deployment. However, this reliance on wired connections tends to be bulky and costly, and can also limit the flexibility of wearable devices [39]. A critical comparison of wired and wireless systems shows that wired transmission offers higher data rate and lower interference but lacks mobility, while wireless transmission enables remote monitoring but faces challenges of energy consumption and signal attenuation in complex agricultural environments (such as leaf shade). Therefore, recent studies are working on the development of wearable sensing systems for plants that are adaptable, have good anti-interference performance, and enable wireless data transmission [88].

Wireless communication effectively avoids the limitations of wired connections and has become an ideal solution for wearable devices. Currently, the mainstream wireless transmission technologies include RFID, ZigBee, Bluetooth, and Wi-Fi, etc., while wireless sensor networks (WSN) integrate these communication functions with sensing modules [14, 89, 90]. However, each wireless protocol exhibits distinct trade-offs in communication range, power consumption, data rate, and environmental robustness, which must be carefully balanced for agricultural deployment. Near-field communication (NFC), a branch of RFID, supports wireless data exchange in both active and passive modes [62]. Recent developments encompass fully printed RFID-based electronic devices and plant surface-mounted sensors, which can send plant stress-response data to cloud platforms for centralized data analysis [91]. Despite their low power consumption and battery-free operation, RFID-based PWSs are inherently limited by short communication distances and susceptibility to environmental attenuation caused by leaf water content and canopy structure. Flexible antennas created through printing or embedding have replaced rigid components, and sensor circuits adopting the ZigBee protocol facilitate remote data transmission [12]. RFID still suffers from short communication range and is easily affected by environmental conditions. Bluetooth offers low cost and reduced power demand and is therefore widely applied in PWS systems. One example is a flexible Bluetooth device that supports real-time wireless monitoring of plant moisture levels on mobile phones [92]. Nevertheless, bluetooth-based systems remain constrained by limited communication range and potential signal interference in dense planting environments, restricting their scalability beyond small plots or greenhouse settings. Wireless sensor networks provide another solution by linking multiple nodes to monitor several parameters at once. A leaf-clip device combined with a soil moisture sensor has even been used to automate irrigation and deliver real-time data for precise water regulation [93]. However, the large number of distributed nodes significantly exacerbates system-level energy consumption and maintenance complexity while substantially expanding the attack surface, posing severe challenges for long-term unattended operation in agricultural fields [94–98].

Generally, although wireless communication technology makes PWS have good scalability, there is no communication protocol that can perfectly meet all the requirements of transmission distance, power consumption efficiency, environmental robustness, and maintenance-free operation at the same time. Future PWS platforms are likely to rely on hybrid communication architectures and energy-aware data transmission strategies to achieve stable and efficient data links in complex agricultural environments.

3 Materials and fabrication strategies for PWSs

3.1 Materials selection

PWSs typically consist of three major parts: a substrate layer, a sensing electrode layer, and a packaging layer. Each layer performs a different function and therefore requires different material properties. To operate reliably on plant tissues, these systems must conform to curved and irregular surfaces, which calls for materials with high flexibility and strong stretchability that allow stable attachment without damaging the plant [99, 100]. Unlike human wearable electronics, plant-wearable materials must additionally accommodate continuous growth, anisotropic deformation, and prolonged exposure to outdoor environments, which significantly constrains material selection and design. The following sections examine the properties, selection principles and recent progress related to these three layers, offering an overview of current material strategies and ongoing developments in PWS research.

3.1.1 Substrate and packaging layers

As the structural support and protective shell of plant-wearable sensors, the substrate and the packaging layers are essential for maintaining device stability and operational safety. Because plant tissues are easily damaged, materials selected for these layers must provide strong biocompatibility, mechanical robustness, tolerance to acidic/alkaline conditions and high ductility.

Frequently employed substrate and encapsulation materials comprise polyethylene terephthalate (PET), polyimide (PI), PDMS, parylene-C, Eco-flex, fiber fabrics, and paper [101–103]. In many designs, the same material is used for both the substrate and the outer encapsulation, although the packaging layer may require added optical or functional properties. Among these materials, elastomers such as PDMS and Eco-flex are particularly favored for PWSs due to their low modulus and high strain tolerance; however, their relatively poor gas barrier properties and long-term environmental stability remain concerns for outdoor deployment. PI, PDMS, PET, and hydrogels are frequently employed because they combine transparency with flexibility and long-term durability. One representative example is a self-winding flexible electrode that exploits the modulus contrast between PDMS and Eco-flex to achieve continuous, nondestructive monitoring of sap flow, illustrating how substrate selection directly influences device adaptability [11].

However, conventional substrate-based materials that are adhered to plant surfaces often suffer from poor conformability (failing to fit tightly to irregular structures like leaf veins or stem protrusions) and limited bio-compatibility, which together restricts the long-term stability of PWSs. To tackle these key challenges, a double-network hydrogel fabricated from acrylic acid, rGO, and PANI has been developed to improve these shortcomings. This material conforms closely to plant tissues, enhances compatibility, and supports simultaneous tracking of growth and ammonia levels [104]. In addition, fueled by the need for sustainable agricultural technologies, biodegradable polymers such as polyvinyl alcohol (PVA), polylactic acid (PLA), polycaprolactone, and silk fibroin are attracting growing interest in the design of eco-friendly sensors [105, 106]. Despite their excellent biocompatibility and conformability, hydrogel-based substrates often suffer from dehydration and mechanical degradation over long-term field operation, necessitating further material optimization.

In addition to substrate-based electrodes, freestanding carbon-based materials such as graphene films and foams offer a promising direction for high-performance plant wearables. These self-supporting materials integrate high conductivity, flexibility, and mechanical robustness in a single layer, avoiding interface failure and strain mismatch during plant growth. For example, bioinspired graphene/Eco-flex Janus films exhibit excellent conformal adhesion and stable electrical performance under strain [107], while vertically aligned graphene foams combine compressibility, high thermal conductivity, and porous gas-permeable structures suitable for adaptive plant contact and stable signal transfer [108]. Their structural integrity, durability, and biocompatibility support long-term *in situ* monitoring of plant physiology and environmental interactions.

3.1.2 Sensing layer

The sensing layer of PWSs serves as the core interface for the specific recognition and acquisition of plant physiological signals and environmental changes. As a key component of the system, the sensing electrodes must maintain high electrical conductivity, chemical durability and biocompatibility to support precise, stable data acquisition and enable long-term, continuous monitoring. However, achieving high sensitivity while preserving mechanical compliance and long-term stability remains a central challenge in sensing material design for PWSs. Metals, carbon-based materials and conductive polymers are the primary categories of sensing materials.

Metal-based sensing materials including pure metals, metal alloys, and metal oxides exhibit excellent electrical conductivity, high chemical stability, and precise responsiveness yet are intrinsically stiff. These materials possess a high Young's modulus and limited elastic strain capacity (2%–3%), rendering them susceptible to fracture under mechanical deformation [109, 110]. To address these limitations, various strategies have been employed, such as designing wrinkled metal films, reducing metals to the nanoscale, or using liquid metals to impart mechanical compliance [111]. For example, gallium-based liquid metal electrodes prepared through hydration-assisted transfer printing have been integrated into a plant-machine interaction platform, enabling early-warning applications [112]. Liquid metals (such as Ga-In-Sn alloys) overcome the rigidity issue due to their fluidity at room temperature, but their high surface tension requires surface modification (such as oxidation and polymer encapsulation) to ensure stable adhesion to plant surfaces. While metal-based electrodes provide excellent conductivity and signal fidelity, their intrinsic rigidity necessitates structural or compositional modification to avoid mechanical failure during plant growth. Carbon-based nanomaterials, such as CNTs, graphene, carbon black, MXene, and carbon nanofibers, have been widely used to develop multiscale and multifunctional sensors due to their high specific surface area, excellent electrical conductivity, and the flexibility to be constructed into multifunctional structures, such as one-dimensional (1D) fibers, two-dimensional (2D) films, or three-dimensional (3D) frameworks. In addition, in order to improve problems such as the susceptibility of metal nanomaterials to oxidation, researchers have also compounded metals with graphene to form hybrid materials with more stable properties [113, 114]. The sensing mechanism of carbon-based materials is rooted in their electronic structure; for example, gas adsorption on MXene surfaces modulates interlayer charge transport, while strain-induced structural changes in CNT networks alter conductivity. Compared with metallic electrodes, carbon-based materials offer improved flexibility and environmental tolerance, albeit sometimes at the cost of higher contact resistance and signal variability.

Conducting polymers, such as polypyrrole (PPy) [49], PANI [73], and PEDOT [115], are often used in combination with carbon or metal nanomaterials in order to simultaneously achieve good flexibility, stretchability, and electrical properties [49, 73, 115]. These composite systems are able to integrate the advantages of each component to prepare flexible electrodes that are both highly sensitive and mechanically durable. In addition to synthetic polymers and nanomaterials, recently researchers have begun to focus on biomass-derived carbon materials, which have great environmental value in sensing element replacement [116]. Examples include carbonized cellulose, lignin, and chitosan, which exhibit good electrical and mechanical properties along with biodegradability and environmental compatibility, characteristics that are particularly applicable for long-term monitoring in agricultural scenarios.

3.2 Fabrication techniques

Fabrication techniques are critical for ensuring the reliable deployment and conformal adaptability of PWSs in agricultural environments, directly determining their ability to meet complex agricultural demands. Importantly, fabrication strategies must balance structural precision, scalability, and plant compatibility, as techniques optimized for laboratory prototypes often face limitations in large-scale agricultural implementation. Moreover, achieving conformal attachment to plant surfaces, ensuring long-term stable monitoring, avoiding tissue damage, and balancing large-scale application costs remain critical for practical deployment. Based on technical characteristics, PWS fabrication methods are categorized into three core types: film preparation, micro-nano patterning, and microneedle structure fabrication. Each category requires coordinated design around the key goals of low invasiveness, high adaptability, and high performance. The following sections will elaborate on the specific implementation paths and application features of these three technical approaches.

Film preparation is a fundamental process in constructing PWSs and can be achieved through techniques such as spin coating, sputter deposition, thermal evaporation, sol–gel processing, and chemical vapor deposition (CVD). To obtain a conductive film, LIG, as a representative of Laser direct writing, is always used. LIG is a rapid manufacturing technique that utilizes the photothermal effect of a laser to directly convert carbon-containing polymers (such as polyimide) into porous graphene in a single step under ambient conditions [117]. By precisely controlling laser parameters (such as focus), the crystallinity and conductivity of graphene can be optimized [118], while forming a distinct vertical gradient structure [119]. This enables mask-free patterning of complex designs, making it particularly suitable for the direct fabrication of customized flexible sensors. As illustrated in Fig. 4(a), a phenolic-resin film containing $FeCl_3$ was deposited onto a PDMS substrate by spin coating. Laser direct writing was then applied to convert the coated layer into a three-dimensional porous graphene structure [11]. An Eco-flex silicone precursor was subsequently spread over the patterned LIG surface, cured and peeled away to obtain an Eco-flex/LIG composite electrode. Benefiting from the inherently low surface energy of PDMS (≈ 30 mN/m), complete pattern transfer was realized. The resulting composite electrode was then inverted and laminated onto a pre-stretched (30%–200%) Eco-flex film. Upon release of the pre-strain, the interfacial strain mismatch induced spontaneous curling into a helical configuration, with the curvature precisely governed by the applied pre-strain. The self-winding mechanism is driven by the elastic recovery of the pre-stretched Eco-flex film, which generates a bending moment that causes the composite electrode to curl, this design eliminates the need for adhesives, reducing plant tissue damage and improving long-term stability.

The electrochemical anodization method creates oxide layers on liquid metal surfaces by applying a controlled electric field. By tuning parameters such as voltage and anodization duration, oxide films with thicknesses of several hundred nanometers can be produced (Fig. 4(b)). As the oxide layer develops, internal stresses arise within the material, and these stresses lead to surface instabilities that form micron-scale wrinkle patterns with height variations on the order of hundreds of nanometers [111]. By altering the geometry of the underlying substrate, the distribution of mechanical stress can be adjusted to generate different wrinkle arrangements, including 1D stripes or 2D labyrinths. Variations in surface tension can also introduce tangential stresses that produce radial wrinkling, allowing multiple hierarchical wrinkle structures to appear simultaneously at different length scales [111]. Fabrication of PWSs can also be achieved by laser micromachining (Fig. 4(c)). A 6 μm-thick copper film is first laminated onto a glass substrate, followed by direct laser cutting to define serpentine conductive traces. Subsequently, a 1 μm-thick PI layer is spin-coated to encapsulate the circuit, after which a secondary laser cut exposes the pad regions for soldering the positive temperature coefficient (PTC) thermistor and temperature sensor chips. Finally, the device is encapsulated with a 10 μm-thick breathable PDMS film and transferred to the plant surface via water-soluble tape after peeling from the substrate [120]. Overall, it is evident that the spin-coating process has become a widely adopted fabrication approach due to its low equipment requirements, facile process control, and compatibility with dopant incorporation.

Besides, sputtering deposition involves bombarding a target with high-energy particles to eject atoms, which subsequently deposit onto the substrate surface to form a thin film (Fig. 4(d)). This technique is widely employed to fabricate conductive layers for plant flexible sensors, yielding films with uniform micro-structures, high packing density, and strong interfacial adhesion to the substrate [12, 121]. Chemical deposition approaches rely on redox reactions to deposit electrode materials onto substrates and include

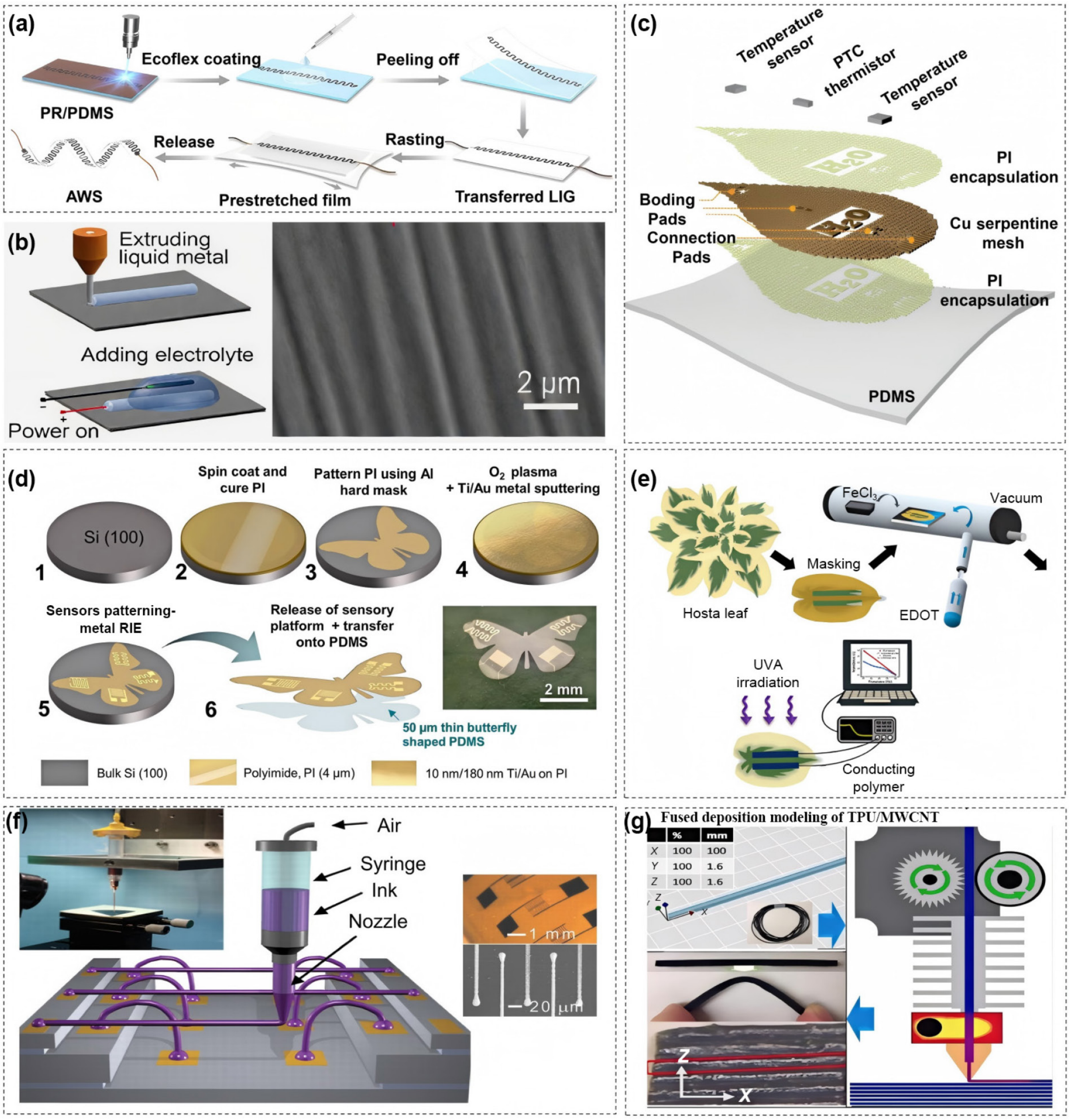


Figure 4 Techniques for fabricating thin films and micro-nano patterns. (a) Preparation process of laser-induced graphene. Reproduced with permission from Ref. [11], © Zhang, C. et al. 2022. (b) Electrochemical anodization technique. Reproduced with permission from Ref. [111], © Wiley-VCH GmbH 2023. (c) Spin coating and laser cutting. Reproduced with permission from Ref. [120], © Chai, Y. F. et al. 2021. (d) Sputtering deposition. Reproduced with permission from Ref. [121], © Nassar, J. M. et al. 2018. (e) Chemical deposition method. Reproduced with permission from Ref. [123], © Kim, J. J. et al. 2019. (f) Inkjet printing. Reproduced with permission from Ref. [128], © American Association for the Advancement of Science 2009. (g) 3D Printing. Reproduced with permission from Ref. [132], © Elsevier Ltd. 2017.

both vapor-phase and liquid-phase methods. Among the various fabrication methods, CVD offers significant advantages in terms of processing at lower temperatures, precise control of film composition, and structural homogeneity. Recently, it has been shown that CVD can even form "electronic tattoos" directly on the plant surface, thus realizing close-fitting real-time monitoring of physiological status (Fig. 4(e)) [122–124]. In addition, the sol–gel method also has the following advantages: high uniformity of the prepared films, low manufacturing cost, and easy to regulate the reaction process [104, 125, 126]. Although high-resolution fabrication techniques enable precise patterning, their scalability and cost-effectiveness remain key constraints for widespread agricultural adoption.

Micro- and nanopatterning preparation is a key link in the fabrication of flexible electronic devices, and its main methods can be categorized into two main groups: lithography and additive manufacturing. The commonly used techniques for circuit patterning include lithography, screen printing, inkjet printing, and roll-to-roll process [127–130]. Taking inkjet printing as one representative example (Fig. 4(f)), it requires maskless, non-contact operation, and is able to deposit functional inks at a higher resolution, which not only supports rapid prototyping, but also has good material utilization. In addition, the technology is compatible with a wide range of substrates, making it very suitable for large-area flexible electronics manufacturing. Critical comparison of patterning techniques shows that lithography offers the highest resolution (~ 1 μm) but is time-consuming and costly; screen printing is scalable but has lower resolution (~ 100 μm); inkjet printing balances resolution and scalability but requires well-formulated inks with appropriate viscosity (10–100 mPa·s).

Among many techniques, lithography is still the most widely used method in the field of integrated circuits due to its high throughput, excellent resolution and scalability [131]. However, conventional lithographic methods are often insufficient for rapidly adapting new materials to irregular or dynamic environments. In contrast, additive manufacturing is more flexible, especially 3D printing, with more selectivity in material selection, ink formulation, and structural scheme design. For example, 3D printing of composites (Fig. 4(g)) not only demonstrates the manufacturing process, but also its potential to enhance mechanical properties [132]. 3D printing enables the fabrication of complex 3D structures (such as microneedle arrays and porous frameworks) that are difficult to achieve with other techniques, but the layer-by-layer fabrication process results in lower mechanical strength compared with bulk materials. In biologically relevant applications, 3D printing allows for the direct construction of functional architectures or biomimetic devices, offering new possibilities for the development of PWSs. Thus, the choice of fabrication technique is inherently application-specific, requiring trade-offs between resolution, mechanical robustness, scalability, and cost.

Microneedle fabrication, an emerging technology, is receiving attention in the field of plant sensing. It enables minimally invasive monitoring while accurately acquiring target analytes and minimizing damage to plant tissues. Conductive micro-needles are particularly advantageous, as they mitigate brittle fractures during insertion and represent one of the most effective strategies for monitoring key metabolites in plants. Their fabrication generally depends on micro- and nanoscale processing techniques that include lithography, etching, and deposition [133]. Multiple classes of materials have been examined for this purpose, such as silicon, metals, polymer matrices, and hydrogel systems. Silicon, although common in microelectronics, is limited by its brittle nature, higher manufacturing cost, and modest biological compatibility [134]. Metals offer a more economical and robust alternative with acceptable compatibility for contact with plant tissues [135, 136]. Anchoring strategies using micro-needles enable close contact with leaf surfaces, facilitating microclimate monitoring and localized delivery of molecules through attachment, movement, or penetration of leaf tissues. Polymer microneedles are especially appealing due to their superior biocompatibility, scalability, and viscoelasticity, which improve tolerance to shear-induced fractures [137]. Despite their advantages in minimally invasive sensing, microneedle-based PWSs still face challenges in large-scale fabrication, mechanical durability, and integration with wireless systems for field use.

The material selection and manufacturing strategy of PWS depends crucially on how to achieve the best balance between performance, mechanical adaptability, scalability and environmental stability. Future breakthroughs require collaborative optimization of materials and manufacturing processes, rather than isolated improvements of individual components. Multi-scale modeling plays a bridge role here, which links the intrinsic characteristics of materials with the overall performance of the device level, thus providing scientific guidance for material selection and structural design of PWSs.

4 Key indicators monitored by PWSs

Monitoring key physiological and environmental indicators such as water status, growth dynamics, and biochemical signals of plants is essential for understanding crop health and optimizing agricultural management. PWSs provide a powerful platform to capture these parameters in real time through electrical, optical, and biochemical sensing strategies. The following section reviews recent progress in PWS applications, highlighting representative examples in moisture monitoring, growth monitoring, and chemical detection.

4.1 Moisture monitoring

The water status of plants directly affects their growth, as water is involved in several key processes such as photosynthesis, transpiration, and temperature regulation. Therefore, real-time monitoring of whether plants are facing water stress has become one of the important directions in the research and development of PWSs. By detecting humidity changes on the plant surface due to transpiration, the sensor is able to continuously track its water status [92]. Under drought conditions, the transpiration rate and growth rate of plants will sharply decrease, and at this time, such sensors can convert the humidity changes caused by water transpiration into electrical signals, thus realizing accurate and timely irrigation regulation (Fig. 5(a)). Based on the above principles, researchers have developed flexible capacitive humidity sensors, which use a laser-engraved polyimide film and graphene oxide composite of moisture-sensitive materials (Fig. 5(b)). The sensing mechanism is based on the modulation of the composite's dielectric constant by water molecules—GO absorbs water through hydrogen bonding, increasing the dielectric constant and thus the capacitance. This design enhances the sensitivity and stability of the sensor, which is capable of continuously collecting electrical signals from the leaf surface to reflect transpiration dynamics in real time [17].

In addition to humidity-based monitoring, PWSs have also been utilized to evaluate water conductivity by detecting resistance changes under varying humidity conditions, thereby reflecting water transport processes from roots to leaves. These sensing strategies together highlight the potential of PWSs for agricultural water management and can provide accurate, continuous and non-destructive monitoring of water status in crops [18]. The water status of plants is easily affected by changes in the surrounding environment, therefore, the recent research trend is to develop multiparameter sensing systems that can monitor multiple physiological and environmental signals simultaneously. For example, a highly versatile, stretchable and ultrathin leaf sensor has been developed, which integrates multiple sensing units to simultaneously detect multiple metrics such as temperature, humidity, light, and strain [12]. These signals are converted into corresponding impedance changes, thus enabling long-term continuous observation of plants and their microenvironments (Fig. 5(c)).

In addition to water and environment monitoring, research has further expanded to focus on stomatal activity. Stomata directly regulates water balance, photosynthesis and gas exchange in plants. For example, an integrated flexible sensing system based on stacked

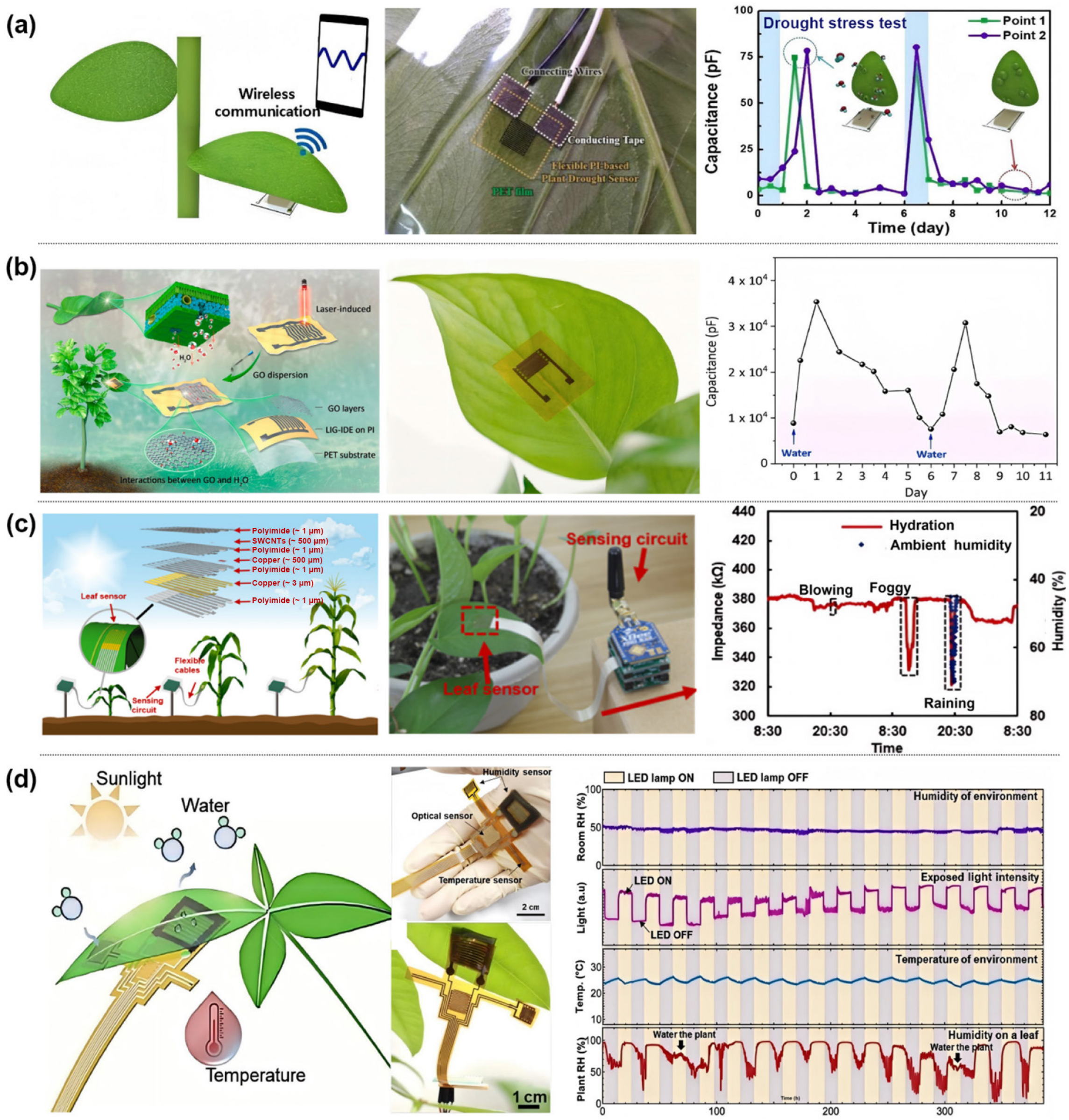


Figure 5 Examples of plant wearable sensors for drought and transpiration monitoring. (a) PI-based drought sensor on leaf surface and tobacco drought response. Reproduced with permission from Ref. [92], © Im, H. et al. 2018. (b) GO-based humidity sensor on leaf surface with real-time capacitance monitoring. Reproduced with permission from Ref. [17], © Elsevier B.V. 2020. (c) Leaf sensor schematic and outdoor moisture results. Reproduced with permission from Ref. [12], © American Chemical Society 2022. (d) Flexible multimodal monitoring device and long-term monitoring. Reproduced with permission from Ref. [16], © American Chemical Society 2020.

$ZnIn_2S_4$ nanosheets has been developed to simultaneously detect light intensity and relative humidity, thereby offering guidance for plant health management by analyzing stomatal behavior (Fig. 5(d)) [16]. Considering the pivotal role of stomata in regulating plant hydraulics and photosensitivity, specialized sensors have also been developed to directly monitor the real-time opening and closure of individual stomata via variations in resistance [138]. The monitoring of these dynamic processes can lay the foundation for in-depth research on the physiological regulatory pathways of plants' adaptability to the environment.

4.2 Growth monitoring

Monitoring plant growth parameters (e.g., stem diameter, leaf size, fruit growth rate) is essential for advancing smart and precision agriculture. Traditional imaging methods are often constrained by environmental variability, whereas flexible sensors offer dynamic, real-time, and continuous measurements. However, growth-related signals typically evolve more slowly than physiological indicators, making their interpretation highly sensitive to sensor placement, mechanical stability, and long-term drift. A wearable growth and environmental monitor for plants has been successfully developed to continuously track leaf surface humidity and temperature, while quantitatively measuring plant growth using a stretchable strain sensor capable of detecting micron-level elongation (Fig. 6(a)). This technology has shown great promise in advancing plant science research and optimizing smart agriculture [121]. Subsequently, a low-cost sensing device has emerged specifically for monitoring the radial growth rate of horticultural crops. The device uses a circular paper-lock structure to wrap a flexible paper tape around the stem of the target plant, successfully enabling growth tracking of round-stemmed crops such as eggplant. However, the device is still large in size and weight, making it difficult to be used for monitoring the growth of soft fruits or irregularly shaped crops [139]. These sensors are currently mostly limited to leaves or regular plant surfaces, and are not yet able to accurately capture the growth dynamics of stems, and thus are still somewhat limited in practical applications. Critical evaluation of this design points out that the paper-based structure is low-cost but lacks stretchability, limiting its application to slow-growing, rigid stems, this highlights the need for elastic substrates (such as Eco-flex and PDMS) for monitoring soft or fast-growing tissues.

Inspired by plant tendrils, an integrated plant-wearable system (IPWS) has been developed using an adaptive winding strain (AWS) sensor that automatically wraps around stems without adhesives (Fig. 6(b)). This design cleverly converts tensile deformation into curvature changes, thus effectively avoiding strain measurement errors due to material cracking [11]. For the growth monitoring of zucchini, eggplant, and other fruits with a large size span, the research team designed a nested "plant bracelet". A stretchable carbon nanotube/graphite composite strain sensor was used, enabling real-time size monitoring from the nanoscale to the centimeter scale (Fig. 6(c)). Notably, this technique revealed for the first time that fruit growth in eggplant and cucurbit plants exhibits a rhythmic pattern, i.e., a short period of rapid expansion followed by a period of quiescence [15].

In the field of plant monitoring, optical PWS has also made a lot of progress recently. A FBG-based sensor system has been developed using flexible silicone clamps to monitor the growth of corn ears [64]. The system, in conjunction with images captured by a camera, can quantify the change in length of the corn cob, thus enabling the assessment of growth from multiple angles. In addition, the device integrates temperature, humidity, and light intensity monitoring modules to synchronize information about the environment in which the crop is located (Fig. 6(d)). The FBG sensing mechanism for growth relies on the Bragg wavelength shift induced by strain. Corn ear elongation stretches the optical fiber, changing the periodic grating structure and thus the reflected wavelength. These advances show that combining optical sensing with other modalities is expected to enable more accurate and real-time continuous tracking of plant growth and the surrounding

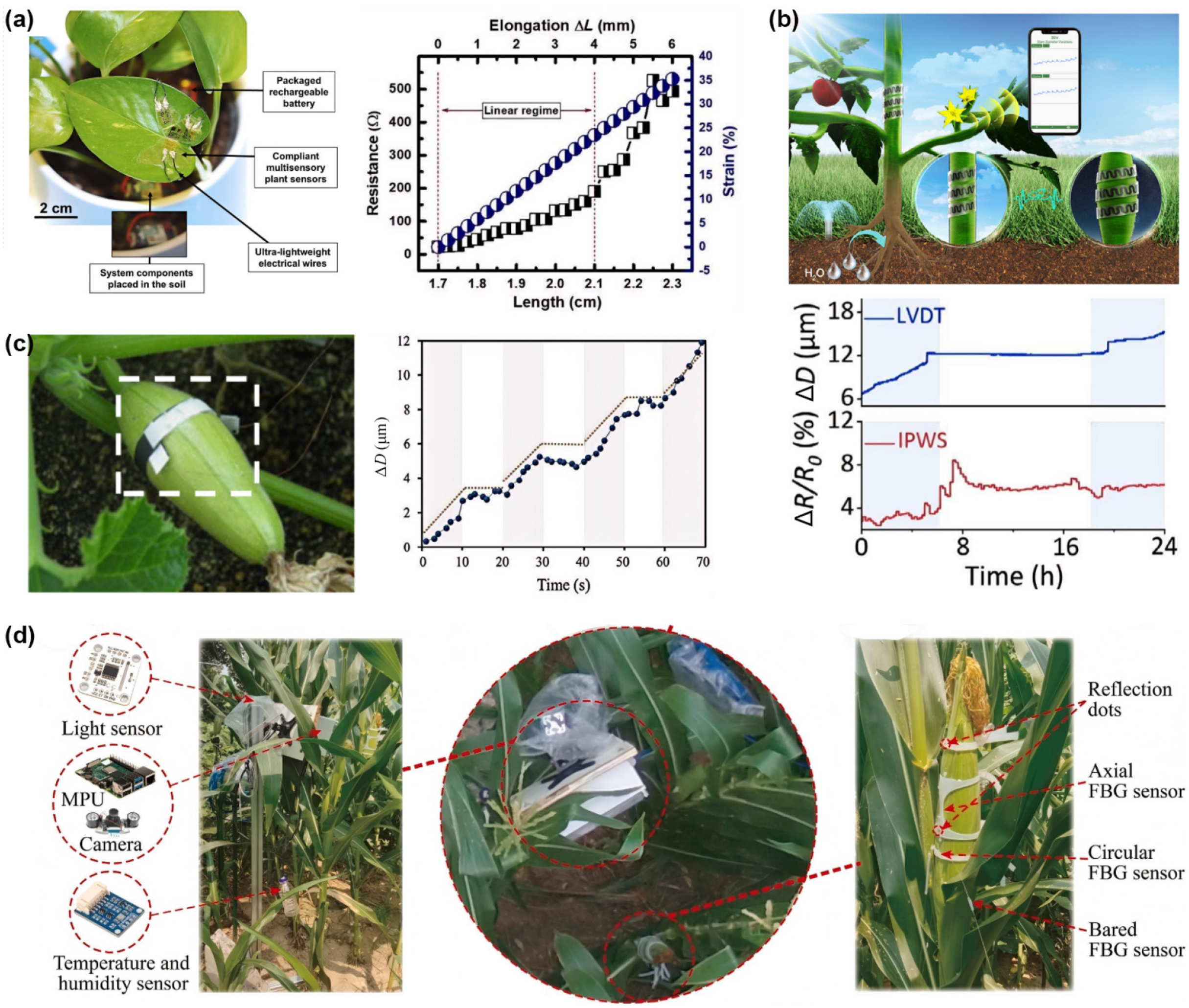


Figure 6 Quantitative plant growth monitoring. (a) Surface mount type of strain sensor for leaf growth monitoring. Reproduced with permission from Ref. [121], © Nassar, J. M. et al. 2018. (b) Wound sensors for monitoring the growth of plant stems. Reproduced with permission from Ref. [11], © Zhang, C. et al. 2022. (c) Ring-fixed sensor for monitoring the growth of fruit stems. Reproduced with permission from Ref. [15], © Elsevier Ltd. 2019. (d) Optical fiber sensors for corn growth monitoring Reproduced with permission from Ref. [64], © Elsevier B.V. 2024.

environment. Mechanistically, most growth sensors rely on strain-induced electrical or optical signal modulation, which necessitates robust mechanical coupling between the device and plant tissue to avoid measurement artifacts.

4.3 Chemical substance monitoring

4.3.1 Volatile substance monitoring

Plants generate a diverse range of chemical signals, both internally (e.g., hormones, metabolites) and externally (e.g., VOCs, ethylene, NO_2, O_3), which act as key biomarkers of physiological stress, pest defense, and environmental adaptation. Compared with physical indicators, chemical signals provide higher specificity but often require more complex sensing interfaces and stricter selectivity control. Traditional detection methods (e.g., gas chromatography and mass spectrometry), although accurate, are usually costly and complicated to operate, making it difficult to be widely applied in the field. In contrast, flexible sensing platforms offer an alternative that is portable, real-time, and non-destructive to plants [22]. A study has designed a PWS for monitoring NO_2 concentration on the leaf surface. The device was constructed with metallic SWCNTs forming a conductive backbone and loaded with a composite layer of AgNPs/rGO as the sensitive material (Fig. 7(a)). The sensing mechanism for NO_2 involves two steps: NO_2 molecules adsorb on the AgNPs/rGO surface, and electron transfer occurs between NO_2 and the conductive network, increasing resistance. This structure enables the sensor to be tightly adhered to planar or curved blades, achieving a very low detection limit while realizing a high sensitivity for NO_2 detection.

In addition to NO_2, O_3 overexposure can cause severe or even irreversible damage to plant tissues, ultimately leading to reduced crop yields. This type of physiological damage is often difficult to detect with the naked eye at an early stage, so it is particularly important to achieve early monitoring. In order to avoid such damage, researchers have developed a conductive polymer "electronic tattoo" prepared by vapor deposition that can be used for *in situ* O_3 detection on the surface of grape leaves [122]. The sensing mechanism relies on O_3-induced oxidation of the conductive polymer (PEDOT:PSS), which reduces conductivity. Meanwhile, the vapor deposition ensures conformal attachment, and the thin film structure (< 1 μm) minimizes interference with plant photosynthesis. This close-fitting sensor can be monitored in the field by impedance spectroscopy and has demonstrated long-term operational stability under ozone-induced oxidative stress (Fig. 7(b)). Notably, it is more resistant to interference from other abiotic stressors and has a long-lasting and stable attachment to the leaf surface, thus providing a continuous, non-destructive means of monitoring O_3-induced cell damage in cash crops.

Methanol is a key VOC released by plants, and its emission level is an important indicator of plant physiological stress and adaptation. Therefore, accurate monitoring of methanol concentrations can help provide insight into plant health and their tolerance to environmental stress. A flexible methanol sensor was incorporated into a microscale gas collection chamber and protected by a hydrophobic and gas-permeable membrane, aiming to mitigate humidity-induced signal deterioration [22]. This design supports direct, *in situ* detection of methanol released from plant tissues and provides a viable way to analyze the dynamics of plant VOCs in real time (Fig. 7(c)). However, in real gas detection, interference from non-target analytes may affect the sensor performance. For this reason, selectivity can be improved by molecular filtration strategies, such as optimizing the pore size of the material to sieve specific molecules, tailoring the surface chemistry to enhance the affinity for the target molecules, or exploiting specific chemical reactions between the sensing material and the target molecules.

Ethylene is a gaseous endogenous plant hormone that is important for regulating key physiological processes such as fruit ripening, breaking seed dormancy, and inhibiting flowering. In a given environment or developmental stage, all organs of a plant may produce ethylene, which makes it an important marker reflecting growth status and stress response. Therefore, realizing real-time *in situ* monitoring of ethylene is of great significance for the development of smart agriculture. To accurately assess fruit ripeness, researchers developed a resistive ethylene sensor based on SnO_2 modified with a nanoscale Cr_2O_3 catalytic layer [20]. The Cr_2O_3 coating selectively catalyzes the oxidation of interfering gases such as CO and H_2 into inert species like CO_2 and H_2O. This approach enhances the sensor's ethylene selectivity while maintaining unobstructed analyte diffusion. The device enabled reliable quantitative assessment of fruit ripeness across five different fruit types. However, this sensor requires high operating temperatures and is rigid, which can potentially cause irreversible damage to the fruits. More innovatively, a fully printed, flexible radio-frequency (RF) resonator sensor fabricated from MXene materials has been developed (Fig. 7(d)). This plant-wearable tag adheres directly to the surface of plant organs and enables wireless, passive, *in situ* monitoring of ethylene emissions [21]. The system provides high detection accuracy and establishes a promising design framework for next-generation wireless and battery-free PWSs. Despite their high sensitivity, gas-based PWSs are generally susceptible to interference from humidity, temperature, and co-existing gases, underscoring the importance of material selectivity and sensor encapsulation.

4.3.2 Pesticide residue monitoring

In addition to environmental and gaseous stressors, *in situ* monitoring of external physical and chemical factors in plants including the detection of pesticide residues is also essential. Compared with laboratory-based analytical techniques, PWS-enabled pesticide monitoring prioritizes rapid, on-site screening rather than absolute quantitative accuracy. These substances are widely applied for pest and disease control as well as for improving crop yields. However, excessive pesticide residues compromise crop safety and can also pose severe health risks to humans, including poisoning and allergic reactions. Conventional analytical techniques such as high-performance liquid chromatography, gas chromatography, and mass spectrometry provide high sensitivity, yet their dependence on expensive instrumentation, complicated procedures, and trained personnel restricts their applicability for rapid and on-site detection.

With the development of flexible and PWS technologies, their application in the field of food safety has received increasing attention. Recent studies have begun to explore the use of wearable devices for *in situ* detection of pesticide residues. For example, a research team has developed a flexible glove-based electrochemical biosensor for rapid *in situ* detection of organophosphorus nerve agent residues on the surface of agricultural products by immobilizing organophosphorus hydrolases [23]. This fingertip-mounted device serves as a portable and point-of-use screening tool, suitable for both food safety monitoring and defense

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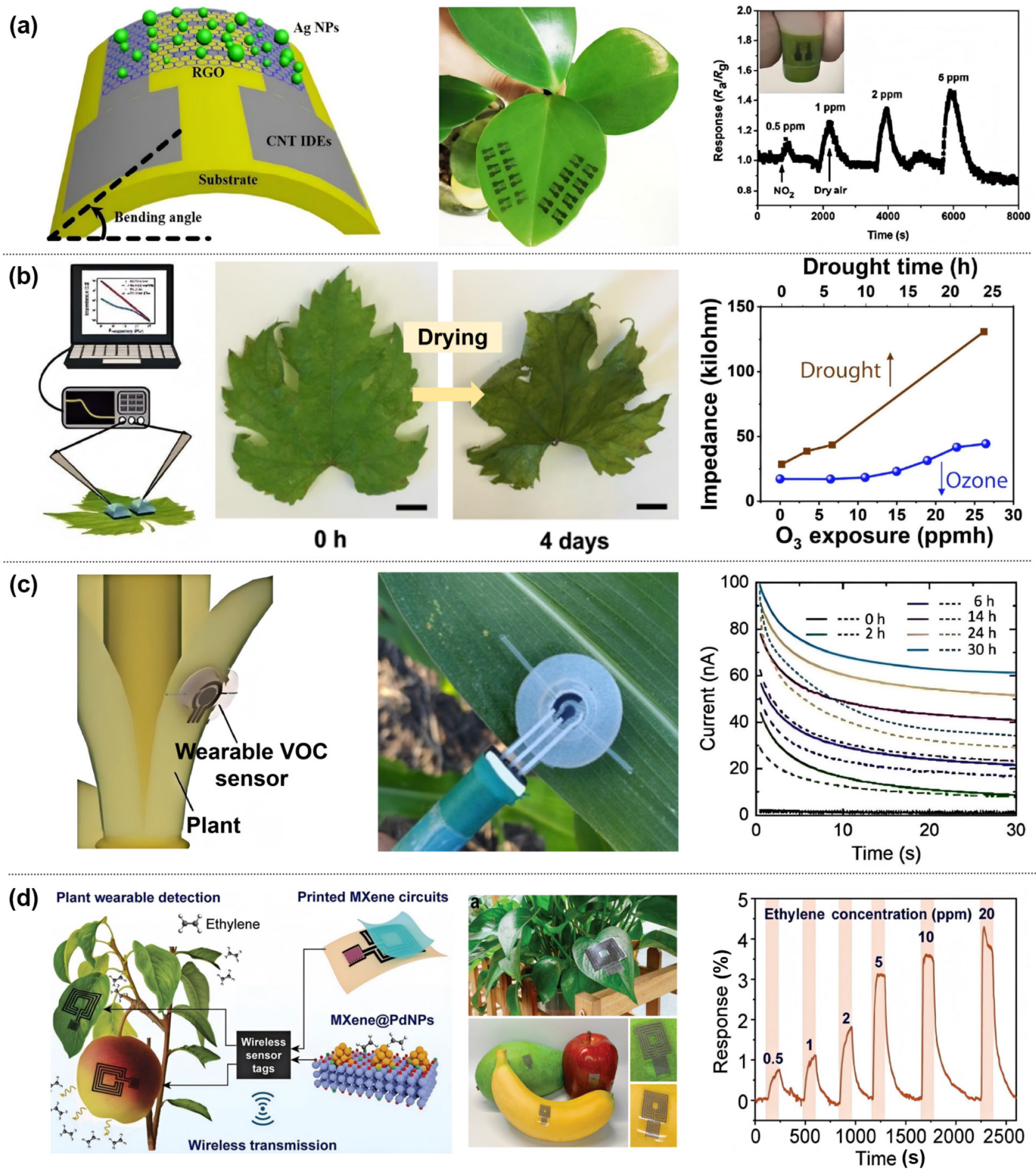

Figure 7 PWSs for gas monitoring. (a) NO_2. Reproduced with permission from Ref. [140], © American Chemical Society 2018. (b) Ozone. Reproduced with permission from Ref. [122], © Kim, J. J. et al. 2020. (c) VOC. Reproduced with permission from Ref. [22], © American Chemical Society 2022. (d) Ethylene. Reproduced with permission from Ref. [21], © Wiley-VCH Gmb 2023.

applications, and represents a promising direction for wearable sensor development. However, although the glove format highlights wearability, it does not directly align with the practical requirements of plant-wearable sensing, as it is primarily designed for human use. To address this limitation, another approach employed LIG technology to construct a flexible serpentine-shaped three-electrode system (Fig. 8(a)). This sensor can fit irregular biological surfaces like leaves and fruit peels, allowing for selective and real-time electrochemical detection of agrochemicals such as methyl parathion, thus serving as a more direct and practical application of PWSs in agriculture [14].

Some key active components in plants, such as hydrogen peroxide (H_2O_2), glucose, and various phytohormones, are important markers reflecting their physiological status and response to environmental stress. However, accessing in-plant chemical information requires minimally invasive interfaces that balance sensing accuracy with tissue preservation. Traditional detection methods usually require destructive sampling of plants and complicated pre-processing steps, which are time-consuming and laborious, and may also interfere with normal plant growth. In recent years, the development of PWS technology has driven the emergence of minimally invasive *in situ* monitoring platforms, which provide new ways to study plant physiology and stress response mechanisms. One representative approach, is the preparation of paper-based electrochemical sensors: detecting reactive oxygen species levels by modifying AuPt alloy nanoparticles on MoS_2 paper [141]. The sensing mechanism relies on the electrocatalytic reduction of H_2O_2 at AuPt nanoparticles, which are supported on a flexible, breathable MoS_2 paper substrate to enhance catalytic activity and achieve a detection limit of 0.1 μM. Excessive amounts of ROS (e.g., H_2O_2) tend to accumulate when plants are damaged or subjected to environmental stresses, so monitoring their concentrations can help to assess the oxidative metabolic status and overall health of the plant. Despite these advances, most of the current implantable or surface-attached sensors are still mainly limited to detecting molecular information at or near the surface of the plant, and it is difficult to obtain in-depth data on the physiological processes inside the plant. This limitation has somewhat hindered the systematic understanding of plant health and stress response.

To fill this gap, microneedle sensors have received attention as an innovative solution. It is capable of minimally invasively penetrating the plant surface and accessing the internal tissues, thus enabling high-precision real-time monitoring of biochemical and physiological signals [142]. Researchers designed an implantable electrochemical probe integrated with six electrodes, including three working electrodes, two reference electrodes, and one counter electrode, which can simultaneously detect H_2O_2, nitric oxide, and pH in plant tissues (Fig. 8(b)). However, the system still relies on a conventional electrochemical workstation and has limitations in portability and field applicability [143]. In addition, nanosensors suitable for real-time H_2O_2 detection have been developed. They can dynamically monitor oxidative stress signals in different species without the need to genetically modify plants, which greatly broadens their potential for application in diverse agricultural scenarios [144].

In addition to monitoring stress-related metabolites, biosensing technologies have also been used for the detection of plant nutritional status. For example, an organic electrochemical transistor (OECT)-based biosensor tracks glucose levels in plant phloem (Fig. 8(c)). When implanted into the vascular tissues of trees, the sensor reflects the dynamics of sugar metabolism in real time and reveals the association between sucrose transport and key physiological processes [145]. These advances suggest that PWSs are no longer limited to surface signal acquisition, but are more capable of probing deeper into the internal biochemical activities,

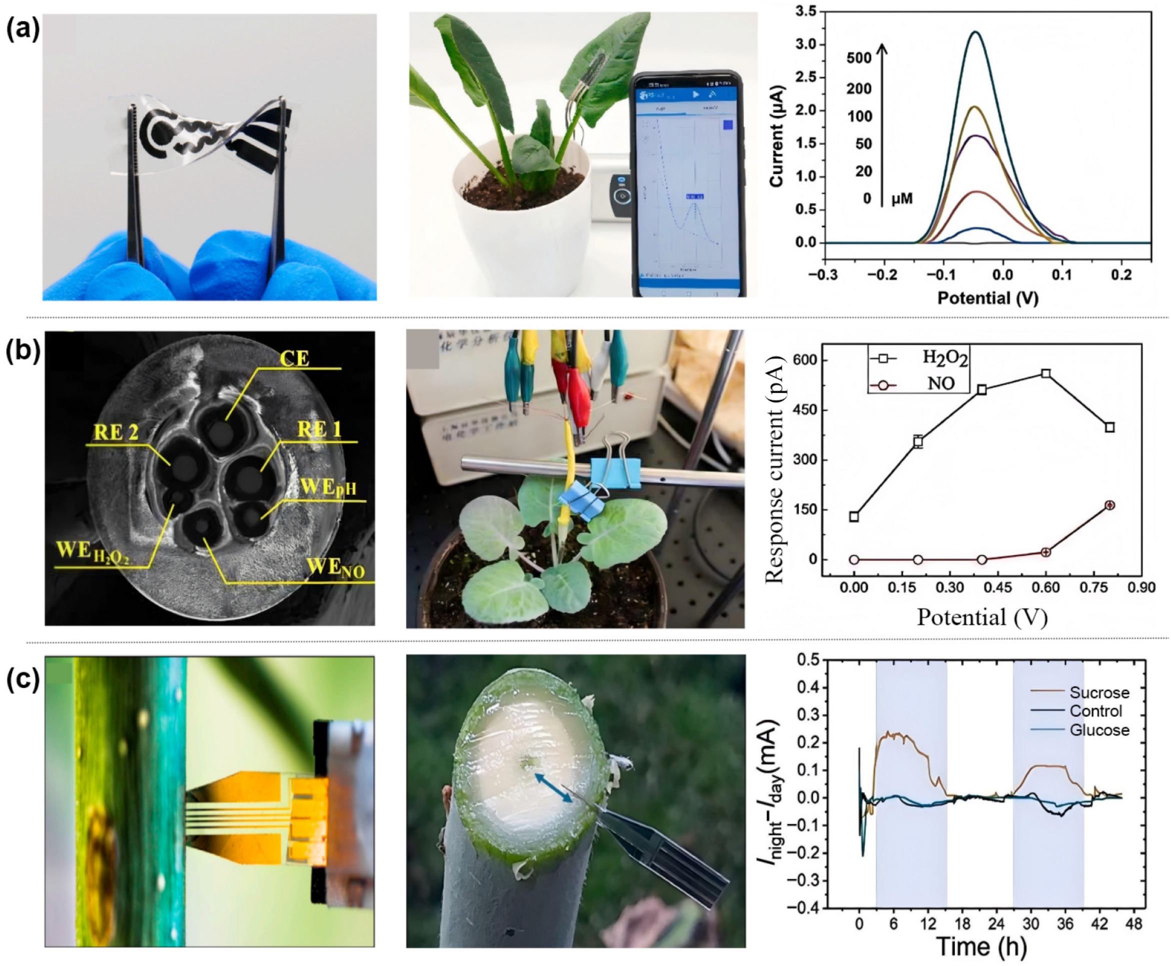

Figure 8 PWSs for other chemicals monitoring. (a) Monitoring of pesticide residue methyl parathion. Reproduced with permission from Ref. [14], © Elsevier B.V. 2020. (b) Monitoring of H_2O_2 and NO. Reproduced with permission from Ref. [143], © Elsevier B.V. 2015. (c) Monitoring of glucose. Reproduced with permission from Ref. [145], © Diacci, C. et al. 2020.

thus providing a more complete perspective for understanding plant health and physiological functions. Although implantable approaches offer deeper physiological insight, their practical deployment remains limited by invasiveness, fabrication complexity, and integration with wearable wireless systems.

In general, various plant indicators have different monitoring priorities, time scales and implementation difficulties. Therefore, an effective PWS design should select a sensing scheme based on specific monitoring targets, rather than pursuing unified acquisition of all physiological signals. The complexity of application scenarios further demonstrates that we need to use multi-scale modeling to integrate sensor data, device behavior, and system-level decision-making to build a more reliable and adaptive monitoring system.

5 Multiscale modeling and simulation

The development of PWSs is inseparable from the combination of experimental innovation and computational simulation. In this, multiple data-driven approaches work together at different scales to drive the process from material design to practical applications. At the atomic scale, DFT provides key theoretical guidance for the design of high-performance sensing materials by resolving the electronic structure and interfacial interactions of materials. At the macro-meso scale, FEA optimizes the structure of PWS device, solving issues like mechanical adaptability to plants and environmental resilience. At the data scale, ML processes PWS-generated datasets for predictive modeling and intelligent agricultural decision-making. Below are details on their specific applications, DFT, FEA, and ML form a synergistic computational framework, accelerating the iteration of PWSs from material screening and device fabrication to intelligent agricultural application.

The multiscale computing method is not an isolated analysis tool, but constitutes a continuous and progressive design process, which promotes the development of PWS from material screening, device development to actual deployment and data interpretation. However, whether the modeling framework can really play a role depends on whether it is closely integrated with experimental verification and real agricultural environmental conditions.

5.1 Atomic-scale material design and screening with DFT-driven

DFT can establish quantitative correlations between microscopic parameters such as adsorption energy and charge transfer and macroscopic properties such as sensitivity and selectivity observed in experiments [146, 147]. Material-level parameters extracted from DFT calculations—such as charge transfer properties, band structure modulation, and adsorption energy—are often used as explicit modeling goals because they are directly related to sensing indicators such as experimentally measurable sensitivity, selectivity, and signal stability [148]. For example, DFT calculations have been used to analyze the adsorption energy and charge transfer behavior between sensing materials and target gas molecules, thereby guiding material selection and functionalization strategies for resistive PWSs [149]. These studies provide a mechanism-level explanation for the sensitivity and selectivity trends observed in experiments.

In practical applications, DFT has been extensively used to explore the interaction between environmental stimuli and sensing materials in PWSs (Fig. 9(a)) [25]. For instance, DFT simulations of gas adsorption on graphene oxide or MXene surfaces have demonstrated how variations in charge transfer and electronic band structures directly influence the resistance or capacitance response, thereby explaining experimental sensitivity to gases such as ethylene or NO_2 [150, 151]. Similarly, the study of the adsorption behavior of water molecules with the help of DFT reveals how hydrogen bonding interactions and surface functional groups can effectively modulate the dielectric properties of materials. This provides an important theoretical basis for the development of high-performance humidity and transpiration sensors [152]. Furthermore, the application of dopants (e.g., nitrogen, sulfur) or defect engineering in nanomaterials has been comprehensively assessed via DFT, demonstrating increased adsorption energies and enhanced specificity for target biomolecules or ions [153, 154].

To achieve a closed loop from DFT prediction of surface chemistry to experimental sensor performance, a quantitative bridge needs to be established between computable microscopic descriptors and measurable macroscopic indicators. To this end, we propose focusing on two core modeling goals: selectivity and stability. For selectivity, DFT calculations should focus on competitive adsorption descriptors, such as the adsorption energy difference between the target gas and the main interfering gas at the active site, which is directly related to the experimental selectivity coefficient. For stability (especially for metal oxide sensors), key descriptors include the formation energy of surface oxygen vacancies and the hetero-interface adhesion work, which dominate the chemical drift and mechanical failure of the sensor, respectively. For instance, DFT predictions that Pd doping enhances SnO_2's CO adsorption energy from −0.47 to −1.69 eV align with experimental observations of a threefold increase in sensitivity [155]; similarly, predictions for Ru-doped TiO_2 are confirmed by a 58% higher humidity response in Quartz Crystal Microbalance (QCM) experiments [152]. These studies form a closed loop of theoretical prediction and experimental validation.

In addition to the above problem-specific calculations, in recent years, the combination of high-throughput density flooding theory calculations with machine learning algorithms has emerged as a powerful strategy for efficiently screening large quantities of candidate materials. This method is capable of rapidly predicting important parameters such as the adsorption energy, electronic properties and stability of materials [156]. This fusion not only ensures the accuracy of first-principle calculations, but also realizes the efficient exploration of large-scale materials, thus greatly shortening the development cycle of novel materials for plant wearable sensing.

5.2 Structural reliability and compatibility design at device scale with FEA-driven

FEA can effectively address the macro- and meso-level challenges encountered in real-world applications of PWSs, with a focus on modeling mechanical reliability and structural adaptability. FEA plays a key role in the connection between material properties and the overall performance of the device—it transforms the intrinsic parameters of the material into deformation and stress distribution information at the system level. Unlike DFT, which focuses on atomic-scale material properties, FEA is mainly used to analyze the performance of PWS as an integrated system in terms of mechanical behavior, heat and mass transfer, which is crucial to address the dynamic interaction between the device and the plant [157]. For example, FEA can be used to predict how the PWS responds to mechanical deformation during plant growth: By simulating the strain distribution of a flexible substrate (e.g., PDMS

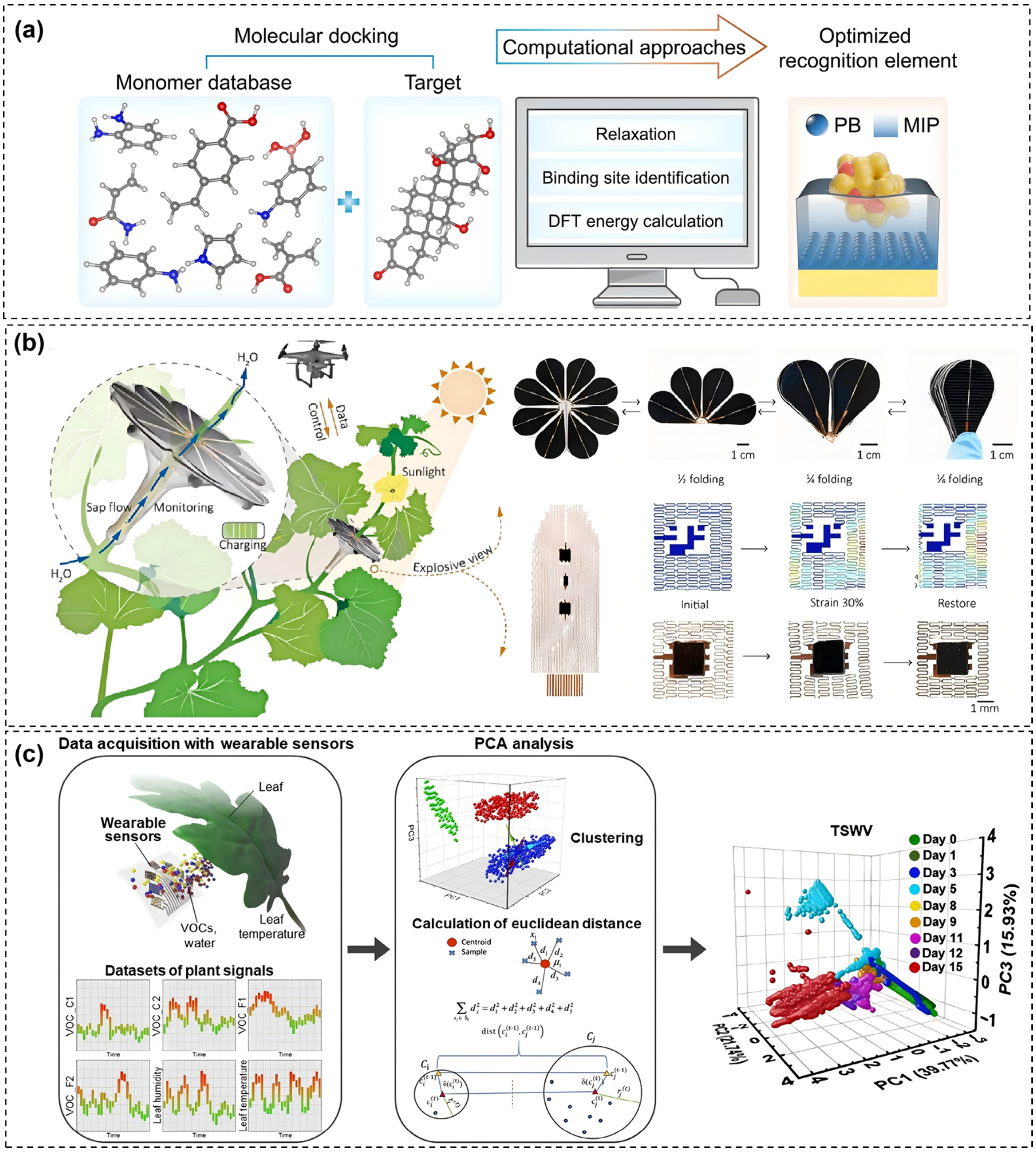

Figure 9 Applications of multiscale modeling on PWSs. (a) Optimization of sensing materials by DFT. Reproduced with permission from Ref. [29], © Liu, Y. et al. 2025. (b) Structural simulation of sensors by FEA. Reproduced with permission from Ref. [160], © Wang, S. et al. 2024. (c) Analysis and prediction through ML based on sensor data. Reproduced with permission from Ref. [26], © Lee, G. et al. 2023.

or Eco-flex material) during bending, researchers are able to optimize the geometrical configuration of the electrodes (e.g., serpentine or cut-paper structural design) in order to avoid cracking or detachment when the stem expands or bends [158]. However, most current simulations still rely on simplified geometric models and static (or idealized) boundary conditions, which may deviate from actual plant growth dynamics and complex environmental loads [159].

In Fig. 9(b), FEA was used to analyze the strain distribution in the critical region of the flexible sensor for the purpose of verifying its mechanical integrity and ensuring that the design is applicable to the actual plant surface. In addition, FEA can assist in designing the system network layout and provide a theoretical basis for its structural design by simulating the stability of the device under deformation caused by growth or environmental factors [160]. FEA also plays an important role in the design of minimally invasive PWS components such as microneedles: By simulating the insertion force and contact stress between microneedles and plant leaf/stem tissues, the tip sharpness, length, and array density can be optimized to minimize damage to plant tissues while ensuring stable contact for metabolite detection [161]. These practices demonstrate that FEA bridges the gap between material innovation in the laboratory and equipment deployment in the field, ensuring that PWS not only performs well in controlled experimental environments, but also remains stable and reliable under complex and variable real-world agricultural conditions.

5.3 System-scale data intelligence with ML-driven

The combination of ML and PWS technologies has become an effective way to improve monitoring effectiveness and promote the development of smart agriculture. With the help of advanced algorithms, raw sensing signals can be processed and transformed into interpretable mathematical models, which can significantly improve data quality by means of denoising, pattern recognition, and predictive analysis [30]. For example, dimensionality reduction techniques such as principal component analysis (PCA) have been used to optimize sensor configurations by eliminating redundant signals while preserving measurement accuracy, reducing system complexity and cost (Fig. 9(c)) [26]. In addition, more sophisticated models such as Long Short-Term Memory (LSTM) networks have been used to integrate multiple sources of data such as soil conductivity, pH, and weather conditions to enable the prediction of soil nutrient dynamics and support low-cost, field-based diagnostics [162]. Similarly, regression-based machine learning models have shown potential in assessing plant water stress, enabling high-precision estimation of leaf water content based on different environmental conditions with root-mean-square errors as low as 0.1%–0.3% [19].

In addition, data mining methods relying on machine learning, such as automatic feature extraction and multimodal data fusion, are able to reveal implicit associations between heterogeneous datasets, such as plant physiology, microclimate, soil chemistry, etc., so that useful information can be discovered more efficiently and accurately than traditional methods. ML has achieved a closed-loop optimization in PWSs, covering aspects such as multi-channel signal analysis, stress warning, and environmental drift compensation. However, the robustness and generalization ability of its model are still limited by the scale, quality, and heterogeneity of agricultural data [163, 164].

5.4 Integration of multiscale modeling into a coherent design pipeline for PWSs

In pursuit of rational design and performance breakthroughs in PWSs, current research is shifting from traditional trial-and-error approaches toward a demand-driven, multi-scale integrated design paradigm. At the core of this paradigm lies the establishment of a digital thread that connects the atomic scale (intrinsic material properties), the device scale (transduction structure and mechanics), and the system scale (sensing information). This process begins with a thorough understanding of the application scenario. First, based on the requirements of the target, the performance indicators at the system level are determined, such as detection sensitivity, biocompatibility, long-term environmental stability, and mechanical strength under dynamic growth conditions. These high-level objectives are then decomposed layer by layer into material-level intrinsic attributes (such as adsorption energy and charge carrier mobility), device-level structural parameters (such as strain distribution and interfacial bonding strength), and system-level signal processing features (such as signal-to-noise ratio and drift-correction models). This decomposition ensures that all modeling efforts, from atomic simulation to system optimization, are closely aligned with and serve the unified end performance goals.

Within this framework, the three key tools of DFT, FEA, and ML transcend their roles as independent toolboxes. Through bidirectional data flows and closed-loop feedback mechanisms, they become deeply coupled, forming a collaborative design ecosystem. DFT screens and designs materials based on fundamental physical principles; FEA translates material properties into manufacturable device models and evaluates their reliability in complex biological environments; and ML acts as the central integrator and optimizer, fusing DFT descriptors, FEA simulation results, and experimental data to construct cross-scale performance prediction models, while also providing reverse guidance for the iterative optimization of materials and devices. This integration transforms multi-scale modeling into a coherent virtual closed loop of "design–predict–verify–optimize", significantly accelerating the development of high-performance, highly reliable PWS for real-world agricultural scenarios.

To concretely illustrate this collaborative paradigm, two studies directly embody the DFT-ML and FEA-ML synergy within PWS research. At the material scale, the DFT-ML synergy enables rational design. A representative study on MXene-based gas sensors employed high-throughput DFT calculations to generate a vast dataset of gas adsorption properties. The data were used to train ML models, creating a pipeline that rapidly predicts the sensitivity and selectivity of new materials, accelerating the inverse design of high-performance sensing layers [156]. At the device and system scale, a breakthrough in bionic PWSs demonstrates the FEA-ML relay. In developing a sunflower-inspired probe, researchers used FEA to simulate strain in flexible circuits, ensuring mechanical robustness on plant stems. Concurrently, ML was pivotal for system functionality: A deep learning algorithm deployed on drones autonomously identified and decoded optical signals from multiple field sensors. This case exemplifies a clear workflow where FEA guarantees physical reliability and ML enables intelligent, scalable data acquisition [160]. These cases provide a validated blueprint, demonstrating that multi-scale tool integration is a practical and essential pathway for advancing PWS design from empirical iteration toward predictable, rational engineering. However, these two examples only represent dyadic collaborations. A significant shortcoming and future challenge is that DFT-FEA-ML within a single, coherent design workflow remains largely unrealized. Current research often features isolated "handoffs" between tools rather than a fully integrated loop with bidirectional feedback. Bridging this gap by creating standardized data pipelines and shared benchmarks to close the loop from atomic prediction to field performance is the critical next step for transitioning PWS design from empirical iteration to truly predictive engineering.

Furthermore, the full realization of this idealized integrated framework still faces considerable challenges. The primary bottleneck lies in the fragmentation of models and data across scales: DFT calculations are often conducted under idealized conditions that differ from real device environments; FEA lacks accurate, dynamic mechanical and physiological parameters of living plant tissues; and ML is constrained by the scarcity of high-quality, standardized cross-scale datasets. Therefore, future progress critically depends on building enabling platforms and standards to support deep collaboration, including: establishing shared cross-scale material–device–environment databases; developing middleware and standardized interfaces to connect models across different scales; and promoting the creation of benchmark cases that integrate both simulation and experimentation. Ultimately, through the development of PWS digital twins that enable continuous calibration and iterative refinement of multi-scale models in a virtual space, currently disparate computational tools may evolve into a truly integrated intelligent design system. Such a system would be capable of guiding design, predicting performance, and optimizing deployment, thereby advancing PWSs from laboratory research to widespread agricultural practice.

6 Comparison between different types of PWSs

The long-term deployment of PWS in real agricultural environments subjects their data reliability to systematic threats from multiple failure modes. Throughout the growing season, delamination can alter the distance between the sensor and the crop canopy, introducing systematic measurement bias; fouling and biofilm formation gradually obscure optical windows, reducing the signal-to-noise ratio, especially after irrigation; UV degradation progressively weakens the structural integrity of the casing and cables; while mechanical fatigue resulting from repeated stress due to wind, rain, and farming operations may lead to fractures or displacement. These degradation modes often act synergistically, and their impact accumulates nonlinearly over time. Mitigation strategies such as regular calibration, upgraded protective materials, and redundant design are essential to ensure data continuity and accuracy throughout the season.

In order to systematically assess the versatility and performance of PWS, a comparative analysis of four mainstream fabrication options was conducted: flexible electrodes with substrates, flexible electrodes without substrates, optical sensors, and microneedle sensors. Each type was systematically evaluated around a number of key metrics covering economy, flexibility, accuracy, consistency, response time, recoverability, lifespan, scalability, and the ability for continuous monitoring (Fig. 10).

Flexible electrodes with substrate, such as those fabricated on PI, PDMS, PET, or paper films, exhibit excellent flexibility and stable adhesion, enabling reliable long-term monitoring of plant physiological parameters including gas exchange and electrical impedance. However, their fabrication processes are relatively complex and costly, which limits their large-scale applicability (Fig. 10(a)).

By contrast, flexible electrodes without substrate, typically realized by direct printing, spraying, or painting conductive inks onto plant surfaces, are low-cost, rapid, and well-suited for on-site applications. Nonetheless, their accuracy, consistency, and durability are often constrained by surface irregularities and environmental fluctuations (Fig. 10(b)).

Optical sensors (e.g., fluorescent probes and fiber-optic systems) are capable of monitoring important metrics such as reactive oxygen species, chlorophyll content, growth status, and water content with high sensitivity and fast response without damaging the plant. Despite the obvious advantages, the high cost of these sensors due to their reliance on complex optical components limits their scale-up in real field environments to some extent (Fig. 10(c)).

Micro-needle sensors, which directly access internal fluids such as xylem or phloem sap, deliver the highest accuracy and consistency for detecting nutrients, hormones, and water potential. However, their insertion into plant tissues introduces mechanical invasiveness and limits flexibility, which reduces their suitability for certain long-term applications (Fig. 10(d)).

Based on the above analysis, each fabrication strategy presents distinctive advantages and limitations: substrate-based electrodes balance stability with flexibility, direct-printed electrodes highlight low-cost and convenience, optical systems maximize accuracy and non-contact monitoring, while microneedles excel in precision at the expense of invasiveness. Therefore, the selection of an appropriate PWS design should be guided by the specific priorities of the intended agricultural application, such as cost-effectiveness, accuracy, durability, or environmental adaptability. In addition to performance comparison, the radar chart in Fig. 10 also reveals several general design principles in PWS selection. Firstly, no single sensor solution can achieve high sensitivity, long-term stability, energy self-sufficiency and system simplicity at the same time, which highlights that there must be trade-offs in the design. Secondly, the robustness and stability of the system are often more important than the peak sensitivity in the dynamic changing real environment (such as open farmland); under controlled conditions such as laboratories or greenhouses, it is more conducive to the use of high-resolution sensing schemes. Finally, even if the selected sensing material itself has excellent performance, energy supply and communication constraints are often the key factors affecting the overall performance of the system.

Detailed application scenarios and performance indicators for the four fabrication strategies are listed in Table 1. Based on the aggregated metrics, a simplified decision-making logic for PWS selection can be outlined. For applications requiring long-term, unattended field monitoring, sensors with high mechanical compliance, low power consumption, and robust wireless communication should be prioritized, even at the expense of ultimate sensitivity. In contrast, for short-term or controlled-environment studies, higher sensitivity and selectivity may justify increased system complexity and energy demand. When biochemical specificity is critical, potentiometric or optical sensing mechanisms are preferred, whereas resistive or capacitive sensors are more suitable for monitoring physical and environmental parameters. These guidelines do not represent rigid rules but rather provide a practical framework to assist application-driven sensor selection under realistic agricultural constraints.

7 Conclusion and perspectives

PWSs have shown great promise for real-time monitoring of plant physiological status. Progress in flexible materials, advanced fabrication strategies, and self-powered energy solutions has greatly broadened their applicability in complex agricultural settings. Furthermore, computational approaches such as DFT provide guidance for the rational design of selective sensing materials, while ML enables multidimensional data analysis, stress prediction, and smart agricultural decision-making. Despite significant progress, the following challenges, including conformability, bio-compatibility, signal reliability, material selection, and manufacturing advancement should be noted:

(I) The irregular, dynamic surfaces of plant organs marked by roughness, curvature, and biological changes like growth or cuticle renewal, often lead to poor PWS adhesion, unstable signals, and reduced sensitivity. FEA serves as a valuable tool here, it can simulate PWS-plant interactions to guide the design of more adaptive, better-adhered devices, theoretically mitigating these issues. However, FEA's effectiveness is limited by inherent challenges, difficulty capturing plants' variable material properties, unavoidable simplifications of complex organ geometries that skew simulation accuracy, and hurdles in validating models against real-world biological dynamics, leaving the design of PWSs capable of adapting to plants remains a long-term challenge.

(II) Existing sensor designs may exert adverse effects on plants in

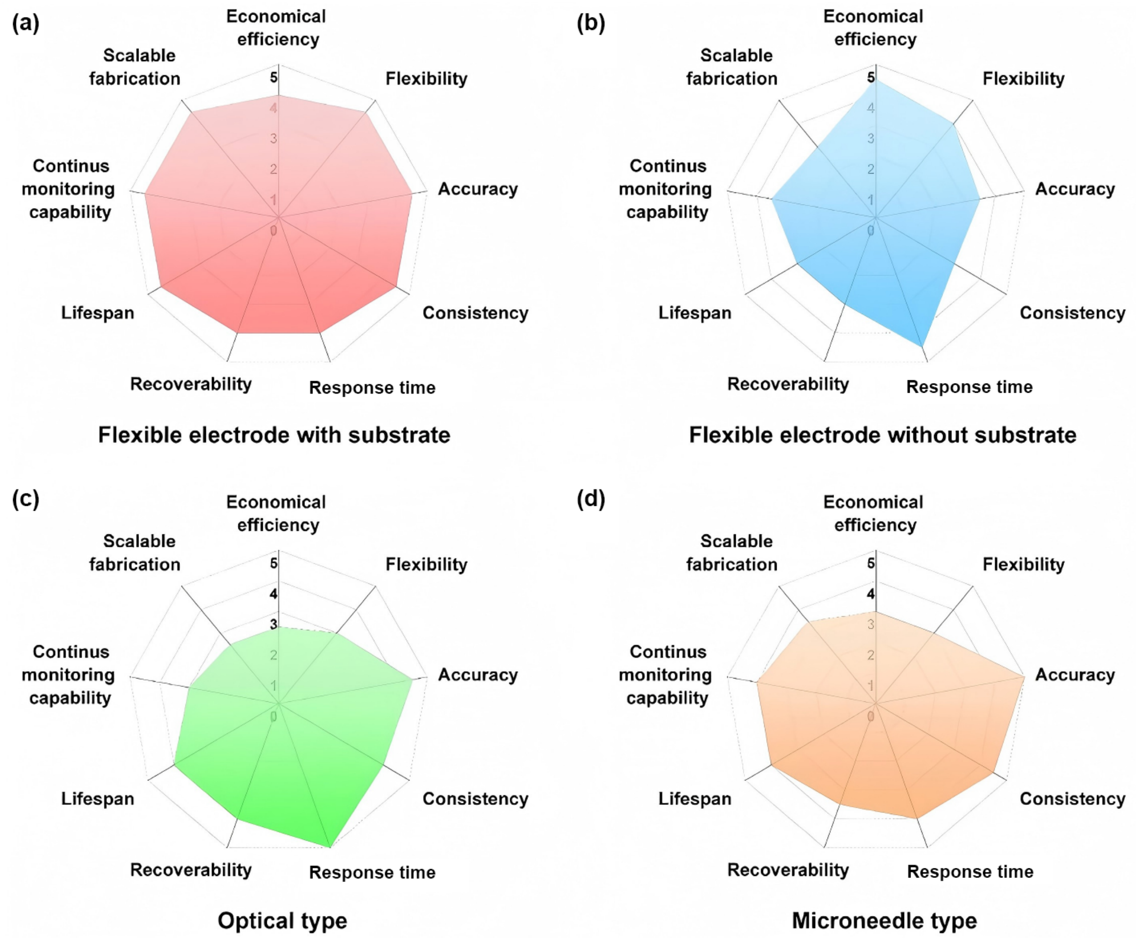

Figure 10 Radar chart of several parameters for different types of sensors. (a) Flexible electrode with substrate. (b) Flexible electrode without substrate. (c) Optical type and (d) microneedle type sensors were compared.

multiple ways. For example, PWS attachment may block light, directly impairing plant photosynthesis. Moreover, PWSs with rigid or sharp micro-structures, such as micro-needle-based wearables, can cause mechanical damage to plant tissues during use; in some cases, insertion sites or damaged tissues may even serve as entry points for local bacterial or viral infections, further compromising plant health. Additionally, certain sensor components may release trace toxic substances, interfering with physiological activities like nutrient absorption and hormone metabolism. Such impacts not only compromise sensor accuracy but may also hinder normal growth.

(III) The core challenge for PWS deployed in fields over months, amidst fluctuating temperature, humidity, and radiation, is sensor drift, which directly leads to unreliable data and hinders their transition from laboratory research to practical applications. The solution strategy is evolving towards multilevel intelligent compensation: at the hardware level, integrating reference sensors for real-time compensation; at the algorithmic level, utilizing machine learning (such as Bayesian neural networks) for drift modeling and online correction; and ultimately, through embedded edge intelligence, enabling the system to autonomously adjust based on environmental changes. The goal is to achieve lifelong reliability without the need for manual intervention.

(IV) The selection and application of materials remain critical challenges for PWSs. Key issues include achieving long-term chemical and mechanical stability, maintaining high sensitivity and selectivity under variable environmental conditions, and ensuring biocompatibility with plant tissues. Rational materials design, guided by computational approaches like DFT, can provide atomic-scale insights, offering a theoretical basis for optimizing sensor performance. However, these predictions must be validated through rigorous experimental testing, as practical conditions and plant material interactions often introduce complexities that cannot be fully captured computationally.

(V) Current fabrication approaches still face challenges in achieving high resolution, conformal adaptability, mechanical robustness, device-to-device consistency, and long-term operational stability. Furthermore, energy supply solutions remain inadequate, with limitations spanning from the development of reliable self-powered energy generation and scalable manufacturing to the seamless integration of power modules into PWSs. Concerns regarding safety, voltage stability, and lifespan of energy storage devices under complex agricultural environment further restrict the practical and sustainable deployment of PWSs in agricultural environments.

(VI) When PWS data are transmitted via cloud platforms and integrated into AI-driven decision systems, cybersecurity, data ownership, and privacy protection become significant challenges. The transmission and storage of data face risks of theft or tampering; the ownership of data (belonging to farmers, service

Table 1 Comparative overview of PWSs reported in recent years

pplication Category	Categories	Materials	Measuring range	Sensor performance	Anti interference capability	Biocompatible	Energy	Communication	Refs.
Water and physiological monitoring	Capacitance	PET, AuNPs	Cap: ~ 1.59–1.77 nF	Bending stable; CV < 1%	Temperature/ humidity/wind resistant	No effect on photosynthesis/ growth	Traditional	Wired	[166]
	Resistance/ capacitance/ current	Silbione RT Gel 4717 (Super Soft Silicone Rubber), PI, CNTs, Cu, porous graphene	Strain: > 120%; *T*: 9–62 °C; H: 0–100% RH; light: 0–100 klux	Temperature coefficient: 1100 ppm/°C; anisotropic strain sensing; fast response	Structurally decoupled; bending-stable	Minimal stomatal impact, no growth hindrance	Traditional	Zigbee	[12]
	Resistance/ current	PI, $ZnIn_2S_4$ (ZIS), SnO_2/CNTs	Humidity: 30%–90% RH; light: 0–120 klux; temperature: 10–50 °C	Stably humidity monitoring (> 15 days); light: 4 ms; temperature sensitivity: 0.032 Ω/°C	Wind/ humidity resistant	Lightweight; no effect on transpiration; stomata normal (15 days)	Traditional	Wired	[16]
	Resistance	PI, PDMS, Cu serpentine	Flow rate: 5–415 μL/min	RSD: 5.66%; R^2 = 0.974; response: 5 min	Temperature/ mechanical/ water resistant	Breathable; no damage after 100 days	Traditional	Bluetooth	[120]
	Resistance/ capacitance	PI, PDMS, GO	Humidity: 22%–96% RH	Peak sensitivity in 22%–96% RH	Humidity-dependent	No damage; no effect on stomata	Traditional	Wired	[170]
	Capacitance	PI, PET, GO/LIG	Humidity: 10%–90% RH	Sens: 3215 pF/% RH; response: 15.8 s; stable	Light/bending resistant	Stomata normal after 10 days	Traditional	Wired	[17]
	Resistance	PI, PDMS, GO, rGO, LIG	Humidity: Dehydration to saturated state	Fast response (< 5 min)	Wind/ temperature/ bending resistant	Breathable; no damage after 100 days	Traditional	Wired	[18]
	Resistance/ voltage	Au/PET film	Relative moisture content: > 60%	Temperature sensitivity: 0.082 Ω/°C; moisture sensitivity: 129.4 kΩ/% RWC; bend-stable	Temperature/ humidity decoupled; bend resistant	Ultra-thin, flexible; no effect on stomata	Traditional	Wired	[171]
	Resistance/ capacitance	PDMS, Au@AgNWs, MWCNTs, Nafion, PI	VOCs: ppm; Temperature: 20–60 °C; humidity: 25%–90% RH	Temperature sensitivity: 0.066%/°C; humidity response: 25 s; accuracy: 99.2%; early detect (+10 days)	Wind/ water/light/ humidity resistant	Biocompatible, non-toxic, lightweight	Traditional /thin-film battery	Wired	[26]
	Capacitance	PDMS, COF films	—	Long-term stable (> 6 months)	Temperature resistance	Biocompatible	Traditional	Wired	[173]
	Resistance/ capacitance/ optical	PDMS, PI, Liquid metal (LM)	Spectrum: 415–680 nm; temperature: 20–40 °C; humidity: 40%–90% RH	Spectral accuracy: 99.2%; humidity sensitivity: 1.6% RH^{-1}; temperature resolution: 0.1 °C; stable	Light/bending/ temperature resistant	Biocompatible, breathable, safe	Traditional	Bluetooth	[67]
Growth monitoring	Resistance/ capacitance/ current	PI, LIG, GO, ZnO	Strain: 0–20 mm; temperature: 5–55 °C	Strain sensitivity: 0.72%/mm; R^2 > 0.98	Structurally decoupled	High air permeability	Traditional	Bluetooth	[167]
	Resistance	Buna-N, graphite /chitosan	Strain: 1%–60%	GF: 64; response < 100 ms	Light-resistant; sealed	Biocompatible	Traditional	Wired	[39]
	Resistance/ capacitance	PDMS/PI, Au, PI	Strain: 0–3; temperature: 20–42 °C	GF: 3.9; cycle-stable (500)	Moisture-resistant	Lightweight, no growth inhibition	Traditional	Bluetooth	[121]
	Resistance	PVA, Ga-based liquid alloy	Growth rate: 2.3 mm/h; humidity: dehydration to saturation.	Fast response	Wind/bending/ humidity insensitive	Leaves healthy after 100 days	Traditional	Wired	[169]
	Resistance	PI, PDMS, carbonized silk georgette (CSG)	Strain: 0.03%–100%; circumference: 0–30 cm	R^2 > 99.7%; RSD < 0.68%; stretch-stable; response < 70 ms	Wind/water-resistant; temperature-compensated	Lightweight; no growth effect; no yellowing after 100 days	Traditional	4G/5G	[174]

(Continued)

pplication Category	Categories	Materials	Measuring range	Sensor performance	Anti interference capability	Biocompatible	Energy	Communication	Refs.
	Optical	PI, FBG fiber	Growth: axial ~ 1.25 mm; radial ~ 5.41 mm	R^2 = 0.974; RSD 5.66%; cycle: ~ 5 min	Humidity/ bending/ temperature resistant	Flexible; no growth hindrance	Traditional	Wi-Fi	[60]
	Optica	PDMS, Silicone (SG), ZnS:Cu phosphor, MWCNTs	Strain: 0%–100%; gestures: 11	R^2 = 0.998; response: ~15 s; cycle-stable (500); auto-calibrated	Color temperature resistant	Breathable, non-cytotoxic	Optical excitation	4G/5G	[65]
	Current	PI/PDMS, MXene/MoS_2/LIG	Concentration: 1–1000 μM	LOD: 0.625 μM	High interference tolerance (50x)	No damage after 100 days	Traditional	Wired	[165]
	Resistance	PI, PDMS, PET, AgNW, GO, PPy	Concentration: 5–25 ppm	Response: 1–2 s; R^2 = 0.993; RSD < 5%	Selective; Stretch resistant	Ultra-thin, flexible; no effect on photosynthesis	Traditional	Bluetooth/Inductive	[57]
	Current	PI, PDMS, LIG, AuNPs, OPH (organophosphorus hydrolase)	Concentration: 0.01–500 μM	R^2 = 0.984; LOD: 0.01 μM; stretch-stable	Selective; Stretch/ humidity resistant	No effect on stomatal	Traditional	Bluetooth	[14]
	Opticl	PVA/AG dual-network hydrogel, CdTe QDs	Concentration: 0.27–200 μM	Response: 2 min; R^2 = 0.98; stable (> 90%, 28 days)	Selective; pH-stable (6–8)	Breathable hydrogel; no leaf yellowing (2 weeks)	Optical (smartphone)	Optical excitation	[62]
Chemical substance monitoring	Optical	SA/BSA dual-network hydrogel, UCNPs@ZIF @PDA	Concentration: 0.02–100 μg/mL	R^2 = 0.97; stable (>90%, 20 days); response < 5 min	Selective; pH-stable (5–9)	Breathable hydrogel; no effect on growth	Optical (smartphone)	Optical excitation	[172]
	Resistance	PET, PDMS, LIG, AuNPs, thiol ligands	Concentration: 0.01–100 ppm	Response < 30 s; LOD: 0.01 ppm; RSD < 5%; stable (>85%, 60 days)	Gas-selective; low wind sensitivity	Non-toxic; nno effect on stomata	Traditional/ Solar-assisted	Wired	[22]
	Resistance	PI, PDMS, rGO, AuNPs, Thiourea ligands, MWCNTs	VOCs: 0.13–3.9 ppm; humidity: 30%–90% RH	Response < 20 s; accuracy > 97%; stable (> 90%, 90 days); low humidity cross-sensitivity < 0.5%	Strain/ temperature resistant	Thin, lightweight; non-cytotoxic	Traditional	Wired	[175]
	Current/ voltage	PI, LIG, PANI	Imidacloprid 0–50 mg/L; salicylic acid 0–13.8 mg/L	R^2 > 0.95; RSD < 6.1%	High interference tolerance (50x)	No effect on photosynthesis	Traditional	Bluetooth	[168]
	Resistance/ capacitance	PI, PDMS, PET, MXene, AgNWs	Strain: 0–100%; humidity: 30%–90% RH; temperature: 10–50 °C; NFC: <10 cm	Conductivity: 6900 S/cm; NFC power; capacitance retention: 90% (3000 cycles)	Bending/ humidity resistant	Non-toxic, no damage, degradable	Battery + Solar + NFC	NFC/RFID/Bluetooth Low Energy (BLE)	[91]
Self-powered and multi-functional systems	Voltage/ current	PTFE/PDMS, Fish gelatin (FG)	Output voltage: 130 V, 0.35 μA; power density: 45.8 μW/cm^2	Cycle-stable (10,000); response <200 ms	Humidity/ deformation resistant	Biodegradable, non-irritating	TENG	Wired	[42]
	Voltage/ current	PDMS, LIG/MXene	Output voltage: ≤ 119 V, ≤ 11 μA; power density: 609.1 mW/m^2	Cycle-stable (10,000); response: 1–2 s; high output	Tensile/ bending resistant	Non-toxic; no effect on photosynthesis	TENG	Wired	[37]

providers, or platforms) must be clarified legally and contractually; and continuous plant physiological and environmental data streams may contain commercially sensitive information, which must be safeguarded through a combination of technical and managerial measures such as encrypted transmission, access control, and data anonymization, in order to establish a reliable and trustworthy agricultural data ecosystem.

(VII) Current PWSs largely rely on chips designed for human or animal applications, whose architecture is mismatched with the inherently slow-varying and high-noise characteristics of plant electrophysiological signals. Future breakthroughs call for the development of plant-dedicated sensor-on-chip systems. This requires hardware-algorithm co-design at the chip level to integrate sensing, processing, and communication, ultimately realizing conformable, miniature intelligent terminals for *in situ* monitoring on plant surfaces.

(VIII) To achieve rational design for plant wearable sensors, the research paradigm must shift from isolated single-scale optimization to cross-scale co-design. The core challenge lies in the current disconnection between material, device, and system-level research, which lacks a unified design thread and data feedback loop that can connect atomic properties, structural mechanics, and field performance. This fragmentation results in prolonged development cycles and difficulties in performance prediction. Therefore, future breakthroughs depend critically on building an enabling platform for cross-scale model and data integration. By establishing standardized interfaces and shared databases, currently fragmented toolchains can be consolidated into a predictable, iterative intelligent design system.

In conclusion, advanced PWSs for smart agriculture rely on targeted innovations that balance technical progress and unresolved challenges. As noted earlier, progress in flexible materials, fabrication, self-powered energy, and computational tools has expanded PWS applicability, yet future development must prioritize key issues: stable conformability with plant surfaces, long-term biocompatibility, reliable multi-parameter monitoring, optimized materials, and solutions to fabrication/energy autonomy limitations. Integrating these breakthroughs with agricultural needs will not only boost crop monitoring precision but also enhance crop productivity, resource efficiency, and carbon reduction, it will also enable sustainable farming via data-driven management and precise interventions, reinforce food security, and support long-term environmental resilience.

Data availability

Not applicable.

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Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

L. L. X.: Writing – review & editing, writing – original draft, investigation, visualization, conceptualization. Y. F. W.: Writing – original draft, resources, data curation. B. H. Z.: Writing – review & editing, writing – original draft, visualization. R. Z. Z.: Writing – original draft, resources, data curation. S. B.: Writing – original draft, investigation. H. Z.: Writing – review & editing, writing – original draft, conceptualization. X. H. Z.: Writing – original draft, formal analysis, visualization. J. H. Z.: Writing – original draft, formal analysis, visualization. J. Q. Q.: Writing – original draft, resources, data curation. B. T.: Writing – original draft, formal analysis, visualization. J. D. H.: Writing – review & editing, writing – original draft, supervision, conceptualization. Z. Z.: Writing – review & editing, supervision, conceptualization. J. F. W.: Writing – review & editing, writing – original draft, conceptualization, visualization, funding acquisition.

Use of AI statement

During the preparation of this work, the authors used DeepSeek for language refinement. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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