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Review

Plant Wearable Sensors: A Comparative Review of Invasive and Non-Invasive Approaches for Real-Time Plant Health Monitoring

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Abstract

Plant wearable sensors have emerged as a transformative technology for precision agriculture and plant phenotyping, enabling in situ, real-time, and continuous acquisition of physiological signals from plant surfaces or internal tissues. However, existing reviews have organized the literature by monitoring targets, sensing functions, or material platforms, without systematically comparing technologies from the fundamental dimension of the degree of intervention imposed on plants. Drawing on representative studies identified through a structured literature search, this review establishes a three-tier classification framework—invasive, minimally invasive, and non-invasive—and conducts a head-to-head comparison across six dimensions: signal characteristics, plant disturbance, long-term stability, manufacturing complexity, field deployability, and biosafety. The results reveal that invasive sensors (nanobionic probes, implantable microelectrodes, and organic electrochemical transistors) achieve nM–pM detection limits, yet wound responses generally limit their effective monitoring duration to the order of days; non-invasive sensors (flexible patches, strain sensors, and multimodal platforms) support weeks-to-months of continuous monitoring and are amenable to scaled deployment, but the indirectness of surface signals confines detection limits to the μM level; minimally invasive technologies (microneedle arrays and ultra-thin microelectrodes) offer a compromise between the two extremes. On this basis, a decision framework based on three-layer selection is proposed to guide technology selection across laboratory research, field deployment, and controlled environment agriculture. Future efforts should focus on standardized performance evaluation protocols, biodegradable self-powered systems, and the integration of invasive–non-invasive hybrid sensing networks with plant digital twins.

Keywords: plant wearable sensors; invasive sensing; non-invasive sensing; minimally invasive sensing; precision agriculture

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1. Introduction

The continuous growth of the global population coupled with adverse environmental factors continues to threaten food security and the development of modern agriculture. It is projected that the world population will reach 9.7 billion, requiring a 60% to 70% increase in food production to meet demand by 2050 [1]. Meanwhile, climate change has exposed one-third of the world's arable land to more severe drought and water stress [2,3]. Half of current irrigation expansion is occurring in water-stressed regions, and the dividends of irrigation expansion are being offset by the unsustainability of water resources [4,5]. Global warming has already reduced staple crop yields by 3% to 8% per decade [6]. Plant diseases alone cause 10% to 30% pre-harvest yield losses in crops worldwide; as climate warming expands the geographical range of pathogens and their insect vectors, these losses are expected to rise further [7,8]. Under the traditional agricultural paradigm, yield increases have long been achieved through expanded irrigation, synthetic fertilizer application and crop-protection pesticides. However, the marginal returns of this production model are steadily diminishing, and 24% to 39% of the world's major cereal-growing regions have experienced yield stagnation [9,10]. Conventional management alone is therefore increasingly insufficient, motivating the shift toward precise and intelligent modern agricultural approaches [11].

Widely adopted agricultural facilities currently monitor both the crop environment and the crops themselves. Environmental monitoring, including meteorological stations [12–16], provides temperature, precipitation, and evapotranspiration data at various spatial and temporal scales, but these are indirect proxies that cannot reflect the physiological status of individual plants [17]. Conventional ground-based multispectral and hyperspectral devices support only discrete single-point sampling and cannot provide long-term, in situ continuous monitoring [18–27]. Satellite remote sensing has greatly expanded spatial coverage through vegetation indices, such as NDVI and EVI, but its revisit cycles and 10–30 m resolution limit fine-scale, early-stress detection at the plant or organ level [28–30]. UAVs equipped with multispectral, thermal, or LiDAR sensors partially bridge this gap by providing centimeter-resolution data [31–35], yet they remain limited by short endurance, weather sensitivity, and airspace restrictions. Traditional plant instruments, such as spectrometer, gas-exchange analyzers, fluorometers, and sap-flow meters, are precise but bulky, destructive, or intermittent, and therefore cannot capture rapid stress dynamics [36–42]. These shared limitations motivate direct plant-surface sensing interfaces, from which plant wearable sensors have emerged with organ- and even sub-organ-scale resolution [43]. Moreover, the destructive and time-consuming procedures required to detect internal reactive oxygen species and nutrient contents make batch testing impractical. These shared limitations have therefore catalyzed a new sensing paradigm in which interfaces are established directly on the plant surface; plant wearable sensors have thus emerged, enabling continuous, real-time acquisition of physiological signals from the plant surface and interior with organ- and even sub-organ-scale resolution [44,45], a capability unattainable by earlier technologies.

Plant wearable sensors are a class of devices that can be directly interfaced with plant organisms through surface adhesion, tissue embedding, or conformal wrapping, enabling in situ, continuous, and real-time acquisition of plant physiological signals. Unlike conventional agricultural sensors, which are limited to monitoring growth environment parameters (soil moisture, temperature, and light), plant wearable sensors employ the plant itself as the sensing substrate.

The development of this research field has followed two distinct technological trajectories. In 2014, Giraldo [46] implanted single-walled carbon nanotubes into living chloroplasts to develop a nanobionic nitric oxide sensor, achieving for the first time invasive plant sensing at the subcellular level. A fundamentally different technical approach emerged in 2018, when Nassar et al. proposed "flexible plant-wearable devices"—flexible electronic patches that conform to the leaf surface and monitor the microenvironment and plant growth status without damaging plant tissues [43]. Since then, both technological trajectories have advanced rapidly, giving rise to multimodal sensing patches adhered to leaves [44], strain sensors wrapped around stems [47,48], and nanomaterial-based probes capable of detecting heavy metals and pesticide [49,50]. Subsequently, researchers have conducted in-depth investigations into the biocompatibility, mechanical compatibility, and long-term monitoring capabilities of various plant wearable sensors, leading to vigorous development of both invasive and non-invasive sensing technologies.

Recent reviews have surveyed plant wearable sensors from complementary perspectives, organizing the literature by monitoring target, sensing function, material platform, or application scenario (Table 1). Collectively, these reviews establish a solid performance-evaluation and fabrication framework, but none adopts the sensor–plant interface as its primary classification axis.

Table 1. Representative previous reviews of plant wearable sensors and the gap addressed by the present review.

Previous Study	Year	Scope	Main Classification Criterion	Interface Invasiveness Addressed?	Ref.
Yin et al.	2021	Soil sensors and plant wearables for smart/precision agriculture	Monitoring target (soil vs. plant)	No	[51]
Xu et al.	2024	Wearable sensors for plant health analysis	Monitored signal (physical/chemical/biological)	No	[52]
Xu et al.	2026	Materials, manufacturing, multiscale modeling, and applications	Material/fabrication	No	[53]
Jamalzadegan et al.	2025	Wearable VOC sensors	Transduction mechanism	No	[54]
Zhou et al.	2024	Electrochemical small-molecule detection	Analyte type	No	[55]
Li et al.	2024	In situ continuous plant health monitoring	Application/system integration	No	[56]
Kuruppuarachchi et al.	2025	Plant wearable sensor advancements	Application/monitored parameter	No	[57]
Chen et al.	2023	Wearable plant sensor progress	Sensor type/parameter/application	No	[58]
Seddaoui & Arduini	2025	Wearable and implantable electrochemical (bio)sensors	Device form (wearable vs. implantable)	Partially	[59]
Park et al.	2025	Non-invasive plant health sensors	Monitored parameter (non-invasive only)	No (non-invasive only)	[60]

The current research framework lacks a classification approach based on the sensor–plant interface itself. Specifically, the choice between invasive and non-invasive schemes involves fundamental trade-offs: invasive sensors offer the advantages of high signal fidelity and access to endogenous molecular information, whereas non-invasive sensors minimize physiological disturbance to plants and are easier to deploy. This trade-off is independent of sensor materials or transduction mechanisms; instead, it directly influences data interpretation for crops, long-term operational stability, and subsequent decision execution. Furthermore, with the emergence of minimally invasive sensing technologies—such as microneedle arrays, biodegradable nanomaterials, and vascular-inserted probes—the boundary between invasive and non-invasive approaches has become increasingly blurred, making it difficult to classify such devices simply into either category. Therefore, a more refined classification system is urgently needed. To this end, this review proposes a three-tier taxonomy—invasive, minimally invasive, and non-invasive—to fill this theoretical gap and clarify the systematic trade-offs that remain unarticulated in existing frameworks. Based on this classification framework, this review aims to address two core questions:

Q1. *How do invasive and non-invasive plant wearable sensors perform across four dimensions—signal quality, physiological interference with plants, long-term stability, and field deployability?*

Q2. *How can a selection decision framework be constructed for different application requirements?*

To this end, Section 2 first establishes the three-tier classification standard. Sections 3 and 4 respectively review representative works on invasive and non-invasive approaches, evaluating their performance characteristics and inherent limitations. Section 5 integrates both technological routes through a head-to-head comparison matrix and proposes a selection framework. Finally, Section 6 summarizes current challenges and provides an outlook on future development.

2. Interface-Based Classification Framework for Plant Wearable Sensors

Based on the barrier characteristics of plant physiology, this section establishes a classification system centered on the sensor–plant interface, proposing a three-tier framework ordered from most to least invasive.

2.1. Biological Basis of Classification

The cuticle on the plant surface is a dense barrier composed of cutin and wax, serving as the first physical interface that sensing elements must breach to enter the plant interior [61]. The biological level at which the sensing interface operates—specifically, whether the sensor penetrates the cuticle and whether it enters living cells—fundamentally determines two mutually constraining attributes: signal acquisition quality (the closer to the signal source, the higher the detection sensitivity) and the degree of disturbance to normal plant physiology [62] (penetrating the cuticle implies disrupting epidermal integrity, potentially triggering wound responses, such as reactive oxygen species bursts and callus formation). The inherent tension between these two factors constitutes the fundamental basis for the classification system proposed in this review.

2.2. Three-Tier Definition

Based on the relative position and penetration depth of the sensing interface within plant tissues, plant wearable sensors are categorized into three tiers (Table 2).

Table 2. Three-tier classification of plant wearable sensors.

Category	Penetration	Interface	Disturbance
Invasive	Cuticle, epidermis, cell wall	Intracellular, apoplast, or vascular lumen/tissue	Severe, triggers wound response
Minimally invasive	Cuticle and superficial epidermis only; avoids viable cells and vascular tissues	Subcuticular/near-surface intercellular space	Mild, transient, largely reversible
Non-invasive	No cuticle penetration	Leaf or stem surface	Negligible

Invasive sensing operates inside living cells or in the apoplast, enabling detection of the lowest analyte concentrations with the fastest response. The trade-off is physiological perturbation—wound-healing responses can alter the local microenvironment over time, causing signal drift.

Minimally invasive sensing breaches only the outermost barriers (the cuticle and, at most, the superficial epidermis), stopping short of both living cells and vascular structures, and captures signals from the near-surface intercellular space through transient, shallow intervention. Reports in this category remain limited and do not yet constitute an independent research branch, but the "compromise strategy" they represent provides a valuable reference for understanding the invasive–non-invasive continuum.

Candidate studies were identified through Web of Science, Scopus, and Google Scholar using keyword combinations, such as "plant wearable sensor," "plant biosensor," "plant microneedle sensor," "invasive," "minimally invasive," and "non-invasive"; titles and abstracts were screened, and 88 studies reporting original sensing data and representative of each interface category were selected for detailed synthesis. The reference list contains 169 sources, including these 88 core studies plus additional works used for background, methodological, and comparative discussion.

Non-invasive sensing operates external to the cuticle, coupling signals through surface attachment or wrapping. It imposes minimal disturbance and supports long-term continuous monitoring. Its inherent limitation is the greater distance between the sensing interface and the physiological signal source, precluding direct access to intracellular molecular information. Its readouts are therefore proxy indicators that require diagnostic inference rather than constituting direct molecular measurements.

2.3. Scope and Caveats

The three-tier framework is an operational tool for systematic comparison rather than a rigid boundary. For example, a shallow microneedle penetrating only the cuticle without reaching the epidermal cell layer is minimally invasive [63,64], whereas a device that does not breach the cuticle at all is non-invasive, and the defining criterion is penetration depth: no cuticle breach is non-invasive; cuticle/superficial-epidermis breach only is minimally invasive; entry into living cells or vascular tissues is invasive. While an injectable nanoprobe designed to degrade after a defined period may exhibit a risk profile closer to minimally invasive strategies [65]. The value of this tripartite classification lies not in assigning every device to a fixed category, but in revealing the regular relationships between sensing performance and plant response across different levels of intervention.

Because the minimally invasive category has not yet accumulated sufficient literature to form a standalone section, this review addresses it as follows: Sections 3 and 4 provide dedicated treatments of invasive and non-invasive sensing, respectively; the minimally invasive tier is presented as an independent dimension in the comparison matrix (Section 5), thereby preserving the completeness of the classification. We begin with invasive sensing technologies.

3. Invasive and Minimally Invasive Sensing Technologies

Although plant phenotyping monitoring can alert to plant stress, rapid compartment-specific dynamic changes occur in hormones, reactive oxygen species, ions and metabolites when plants are subjected to abiotic and biotic stresses. These molecular signals generally precede macroscopic phenotypic changes and serve as early targets for plant health monitoring [66–69]. However, conventional phenotyping approaches—including optical imaging, chlorophyll fluorescence, and destructive sampling—either provide indirect physiological proxies or lack the temporal and spatial resolution required to capture transient chemical dynamics in living tissues [70,71]. Invasive and minimally invasive sensors address this gap by positioning the sensing interface within or beneath the cuticle, in direct contact with the cytoplasm, apoplast, or vascular sap, thereby enabling real-time, in situ quantification of molecular analytes with high sensitivity and selectivity. Despite the trade-offs associated with tissue penetration, including wound responses and long-term stability, these technologies provide a molecular-level observation window essential for advancing from macroscopic phenotyping toward mechanistic plant physiology and precision agriculture.

Invasive and minimally invasive sensing technologies share the common feature of establishing a physical interface that goes beyond surface contact—the sensing element enters the living plant tissue through direct puncture, embedding or implantation (Figure 1). Based on the biological level of the interface and the depth of penetration, this section further subdivides these technologies into two groups: (i) tissue/intracellular implantable sensors, including stem-implanted OECT sensors and biofuel cells; and (ii) minimally invasive puncture-based sensors, and discusses their working principles, representative works, and inherent limitations.

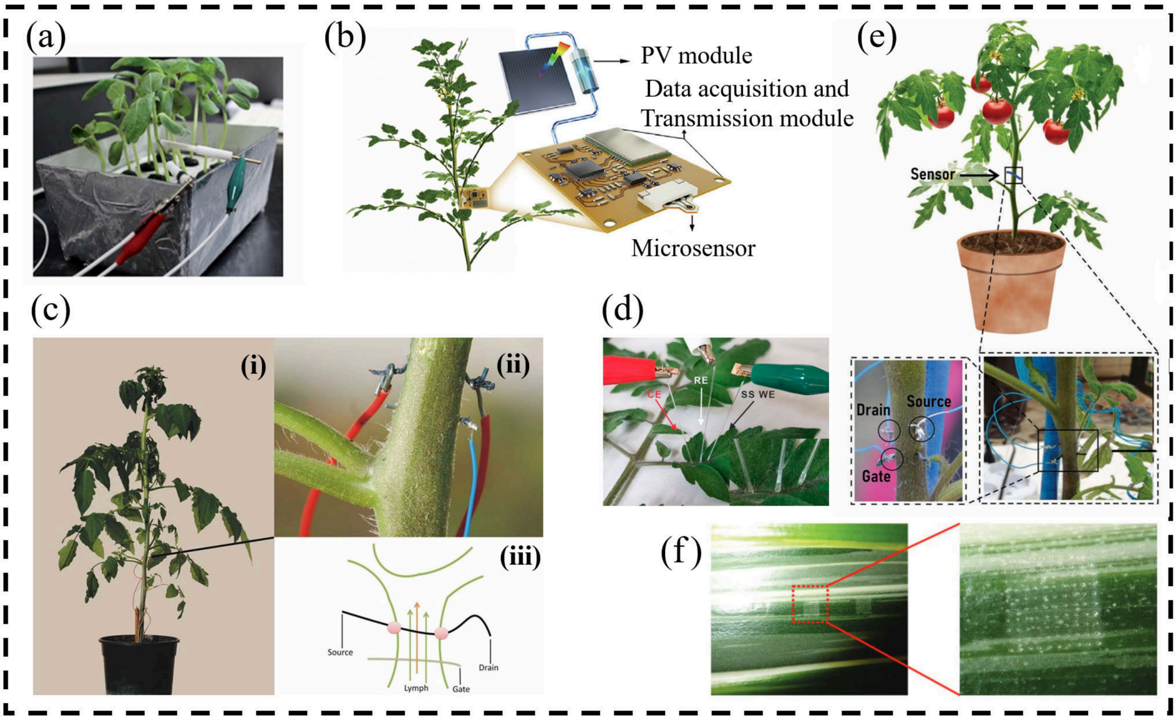

Figure 1. Invasive sensors. (**a**) SA in a sunflower seedling by the PtNF/ERGO/Pt electrode [72]. (**b**) Illustration of the implantable and self-powered sensing system [73]. (**c**) The bioristor integrated in a tomato plant (**i**) Physical image of invasive sensor; (**ii**) Details of sensor; (**iii**) Schematic diagram [74]. (**d**) In vivo and continuous electrochemical monitoring of H_2O_2 in vein of the tomato leaf based on the Au/SS wire-based electrochemical microsensor [75]. (**e**) Detection device for ion concentration and saturation of tomato stems fabricated based on organic electrochemical transistors [76]. (**f**) Traces left after microneedle electrodes puncture leaf organs [63].

3.1. Tissue/Intracellular Implantable Sensors

3.1.1. Plant Nanobionic Sensors

Plant nanobionic sensing integrates functional nanomaterials into subcellular compartments of living tissues, including chloroplasts, apoplast, and cytoplasm, and exploits their optical or electrical transduction properties for in situ, real-time detection of target analytes [45,46,49]. F46. By functionalizing SWCNT surfaces with analyte-specific recognition groups, the same platform has been extended to the selective detection of arsenite, with nanomolar sensitivity and stable operation in planta for more than 72 h [49]. The core advantage of this technology is that the sensing interface shares the spatial scale of the physiological signal source, enabling the highest sensitivity for in situ molecular detection. Its principal bottleneck is that nanomaterial injection itself inflicts tissue damage

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and can trigger defense responses, including ROS bursts, cell wall lignification, and callus formation, which may cause signal drift over time. In addition, the migration pathways, biodegradation behavior, and ecological safety of nanomaterials in plants have not yet been systematically evaluated [45].

3.1.2. Implantable Microelectrode Sensors

Implantable microelectrode sensors rely on microfabricated electrodes inserted directly into specific plant tissues and use electrochemical methods, such as differential pulse voltammetry and chronoamperometry, for quantitative detection of target molecules. Based on the detection target, these sensors can be subdivided into phytohormone sensors, ROS sensors, and inorganic ion sensors.

Phytohormone microsensors have progressed from single-electrode demonstrations to tissue-compatible implantable devices. Salicylic acid (SA) has been quantified in sunflower stems and other plant tissues with platinum nanoflower/electrochemically reduced graphene oxide microelectrodes (500 μm) and self-supporting nitrogen-doped graphene microelectrodes (300 μm), with linear ranges of 100 pM-1 μM and 1–500 μM, respectively, and picomolar to submicromolar detection limits [72,77]. Indole-3-acetic acid (IAA) has been detected in soybean stems using polymer/platinum nanoparticle/reduced graphene oxide/gold nanostructure-modified stainless-steel microsensors (250 μm), with a detection limit as low as 43 pg/mL [78]. Abscisic acid (ABA) has been monitored in planta with Au@SnO_2-vertical graphene microneedle sensors (700 μm), achieving detection limits of 0.002–0.005 μM within a dynamic range up to about 495.2 μmol/L [79]. Beyond hormones, silk-fibroin microneedle patches have been used to sample plant interstitial fluid for glucose detection, with a linear range of 30–180 mmol/L and a sensitivity of 1.22 nA/mmol [65]. Together, these studies show that sub-millimeter implantable electrodes can provide real-time phytohormone and metabolite information with minimal sample preparation, although electrode diameter, tissue compatibility, and calibration remain application-specific.

For ROS and multi-parameter monitoring, continuous in vivo measurements have been demonstrated at both tissue and single-cell scales. Nano-gold-modified stainless-steel wire microelectrodes (100 μm) inserted into tomato leaf veins enabled continuous H_2O_2 detection from 10 to 1000 μmol/L while causing relatively little damage to the plant [75]. Hemoglobin/SWCNT-modified carbon-fiber ultramicroelectrodes (7 μm) tracked salinity-induced oxidative bursts in aloe leaves with a detection limit as low as 4 μmol/L [80], and Nafion/Pt microbundle electrodes (1000 μm) achieved simultaneous real-time monitoring of H_2O_2, NO, and pH for up to 45 h [81]. At the single-cell level, platinum nanoparticle-modified carbon-fiber microdisk electrodes resolved oxidative bursts from individual protoplasts, revealing quantal release characteristics and numerous transient micro-oxidative-burst signals after pathogen-mimic induction [82]. These results demonstrate that electrochemical microsensors can span tissue-scale and cellular-scale ROS dynamics, although the diversity of electrode materials and measurement protocols still limits cross-study comparability.

For inorganic ion detection, needle-shaped MEMS sensors based on photosensitive epoxy bioresin (SU8/graphene oxide/vitamin B12) enabled amperometric nitrate quantification in plant stems, operating stably under both light and dark conditions and distinguishing nitrogen assimilation dynamics associated with photosynthesis without sample pretreatment [83]. Printed organic electrochemical transistors (OECTs) combined with ion-selective membranes have further enabled selective and continuous measurement of K^+ and NO_3^- in whole-plant sap for more than 48 h [84]. These developments indicate that implantable electrochemical and transistor-based sensors are converging toward multi-ion, long-term nutrient monitoring, although membrane selectivity and response kinetics remain limiting factors.

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3.1.3. Implantable Organic Electrochemical Transistor Sensors

OECTs implanted directly into the xylem or phloem of plant stems provide high-gain ion-to-electron transduction. The working mechanism relies on the doping/dedoping effect of the channel polymer, typically PEDOT: PSS, induced by gate voltage variations, which amplifies ionic signals in plant sap into measurable channel currents. PEDOT: PSS-coated cotton fibers threaded through tomato stems enabled continuous monitoring of the circadian rhythm of sap conductivity [74]; biocompatible OECT configurations subsequently allowed quantitative measurement of sap ion concentration and saturation [76]. Glucose oxidase-modified OECTs were used for circadian monitoring of xylem glucose and sucrose concentrations [85], and self-healing, stretchable printed cryogel electrodes improved mechanical adaptability and long-term stability in plants [86]. OECTs are particularly attractive for ion and metabolite detection because of their strong signal amplification, but their selectivity depends on ion-selective membranes, and the inhibitory effect of PVC-based membranes on ion permeation limits response speed and signal-to-noise ratio [84].

3.1.4. Implantable Self-Powered Sensing Systems

Long-term continuous monitoring requires a stable and sustainable energy supply, and implantable biofuel cells and self-powered systems provide a promising solution. A glucose-O_2 enzymatic biofuel cell implanted in a living grape, consisting of two enzyme-modified carbon fibers with glucose oxidase on the anode and bilirubin oxidase on the cathode, achieved a maximum power output of 2400 mW/m^2 at a cell voltage of 0.52 V using endogenous glucose as fuel [87]. Needle-shaped biofuel cells with arrayed anodes were subsequently developed for more practical in planta operation [88]. Because the output of such devices depends heavily on endogenous glucose concentration (>30 mM) and pH (~5.4), long-term power stability remains challenging. An alternative strategy integrates photovoltaic modules with H_2O_2 electrochemical sensors in an implantable, self-powered system that harvests light energy and enables continuous wireless monitoring of H_2O_2 dynamics without an external power supply, with signal drift below 10% within 48 h [73]. These systems can serve simultaneously as sensing probes and energy harvesters, but further improvements in energy density, stability, and biofouling resistance are still required for field deployment.

3.2. Minimally Invasive Puncture-Based Sensors

Minimally invasive sensing technologies are characterized by penetration of the cuticle without entering living cells, with the sensing interface positioned between invasive (intracellular/vascular bundle) and non-invasive (surface attachment) approaches, enabling the acquisition of chemical signals from the intercellular fluid or near-surface layers while minimizing tissue damage.

3.2.1. Microneedle Array Sensors

Microneedle array sensors are the most representative technological route in this category because they access epidermal and intercellular signals through shallow penetration. Microneedle arrays penetrating the leaf cuticle to the epidermal intercellular space enabled real-time monitoring of tissue electrical properties by impedance spectroscopy, with stable operation on leaves for more than 14 days and an average relative noise of 3.83% [63]. Magnetic molecularly imprinted microneedle/interdigitated electrode sensors provided highly selective SA detection with a detection limit of 2.74 μM and a range up to 150 μM [89]. Microneedle patches integrating SERS enhancement substrates enabled in situ capture and detection of thiram and thiabendazole after cuticle penetration [64]. Potentiometric microneedles with ion-selective membranes allowed selective Na^+ detection for salt-stress response analysis [90], while 3D-printed solid microneedle arrays modified with polyaniline enabled continuous real-time monitoring of apoplastic pH in the range 4–8 [91]. Hollow microneedle electrochemical devices further enabled simultaneous in situ detection of glucose and H_2O_2 from tissue fluid extracted through leaf puncture, with validation on four succulent plant species [92]. As a class, these sensors balance minimal tissue damage with stable, potentially field-compatible operation and are especially suited to apoplastic and intercellular targets.

3.2.2. Ultra-Thin Microelectrode Sensors

Ultra-thin microelectrode sensors use extremely fine electrode diameters (1–100 μm) to acquire near-surface chemical signals with minimal tissue damage. Gold-coated cuprous oxide/graphene/polydopamine interdigitated microelectrode arrays with 1 μm electrode dimensions were inserted shallowly into the intercellular space of mesophyll cells in cucumber leaves, achieving real-time in situ SA detection with a detection limit of 1.16 nM [93]. Graphite microelectrodes (100 μm) inserted shallowly into apple tissue enabled in situ electrochemical monitoring of ascorbic acid and polyphenols [94]. In addition, OECTs minimally invasively attached or inserted into leaves have been used to monitor chlorophyll and glucose simultaneously, resolving chloroplast glucose export under two distinct metabolic stages with minute-level temporal resolution and micromolar detection limits, with dynamic monitoring performance improved by an order of magnitude compared with conventional methods [95]. These approaches occupy an intermediate position between intracellular implants and surface-attached sensors, providing molecular information from the intercellular space while largely preserving tissue integrity.

3.3. Advantages and Limitations

The core advantage of invasive sensors lies in their sensing interface being located in close proximity to the physiological signal source, thus offering the highest sensitivity (nM–pM level) and fastest response time (seconds), particularly suitable for real-time detection of small molecules at the cellular/subcellular scale (NO, H_2O_2, SA, IAA, ABA). However, wound responses caused by tissue penetration—including ROS bursts, cell wall lignification [96], and callus formation—can cause signal drift over time. Accordingly, reported invasive monitoring windows are generally limited to the order of days, e.g., 45–72 h across nanobionic, microelectrode, and self-powered systems [49,73,81]. Furthermore, the long-term biocompatibility and ecological safety of nanomaterials and implantable devices lack systematic evaluation [45]. OECT sensors demonstrate excellent signal amplification capability (transconductance reaching the mS level) for ion detection, but their selectivity is limited by ISM performance, and the relatively large device volume (mm scale) constrains application in small plants or delicate tissues. Implantable biofuel cells offer self-powering advantages, but their output depends on endogenous metabolite concentrations and environmental conditions, making long-term stable energy supply difficult to guarantee.

Minimally invasive sensors, by reducing puncture depth (<200 μm) and electrode size (1–100 μm), significantly reduce physiological disturbance while maintaining reasonable signal acquisition capability. Microneedle arrays can operate stably for over 14 days, and ultra-thin microelectrodes (1 μm) enable precise sampling at the single-cell intercellular space. However, their sensing interface is farther from intracellular signal sources (remaining in the intercellular space or beneath the cuticle), resulting in shallower molecular information depth (detection limits typically in the μM–nM range) compared to invasive approaches. Common challenges for both technology categories include: insufficient long-term mechanical and chemical stability at the sensor-tissue interface, lack of standardized calibration protocols across species and growth stages, and a persisting gap between laboratory demonstrations and genuine field validation.

4. Non-Invasive Sensing Technologies

Plants continuously exchange energy, water, and chemical information with their surroundings through their surfaces, making leaf and stem surface signals rich yet indirect indicators of physiological status. Throughout this section, we distinguish three levels of information: (i) direct sensing, in which the measured quantity is the target analyte or signal itself; (ii) proxy sensing, in which a correlated surface parameter—such as leaf temperature, stomatal conductance, VOC emission, or strain—is measured as an indirect indicator; and (iii) diagnostic inference, in which the measured signal, whether direct or proxy, is translated into a physiological conclusion (e.g., water deficit or disease), typically through calibration, mechanistic models, or machine-learning data fusion. In the non-invasive systems described below, surface signals are proxies, and physiological diagnoses are inferences that require additional corroboration rather than direct measurements. Growth deformation, surface temperature, humidity, transpiration, volatile organic compounds and pesticide residues on plant surfaces can be acquired without penetrating the cuticle [97–100], which preserves tissue integrity, avoids wound responses, and supports weeks-to-months of continuous field monitoring—advantages that are difficult to achieve with invasive interfaces [101].

Non-invasive sensing technologies operate with the sensing interface located external to the plant cuticle. Sensing elements achieve signal acquisition through surface attachment, wrapping, or close-range coupling without damaging any plant tissue (Figure 2). Based on the type of signal acquired, we classified non-invasive sensors into physical parameter sensors and chemical parameter sensors, and further discusses multimodal integrated platforms along with their comprehensive advantages and limitations.

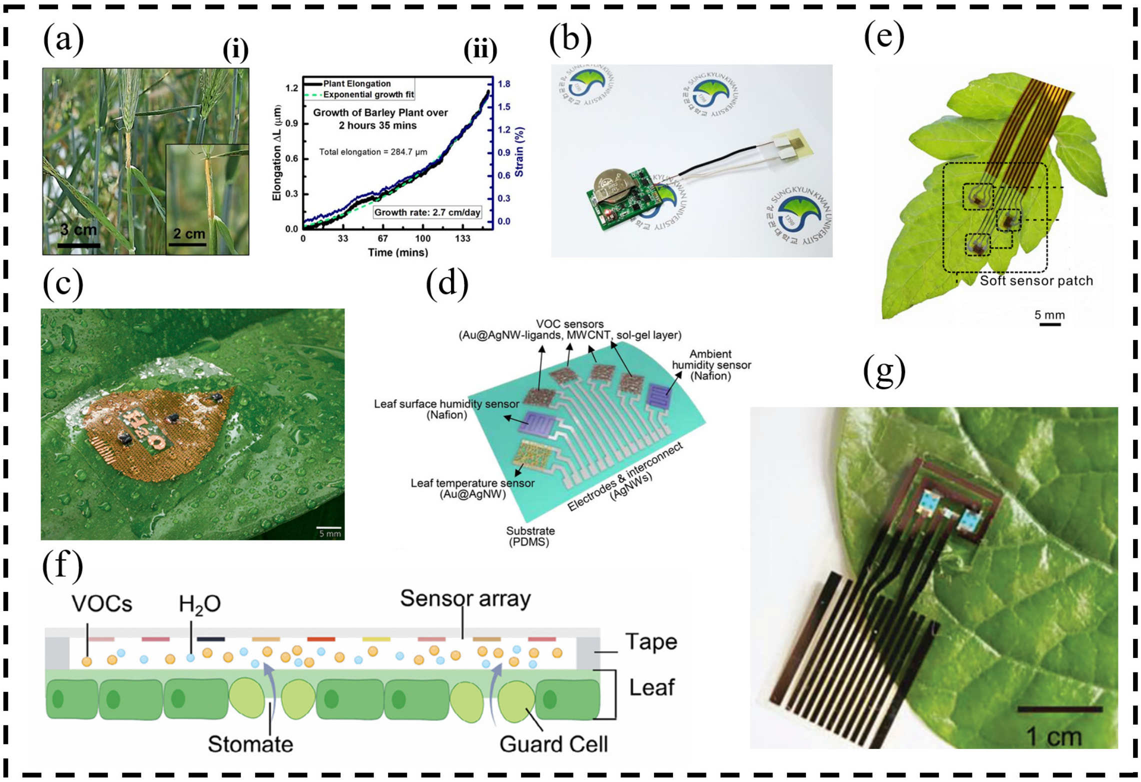

Figure 2. Non-Invasive sensors. (**a**) Quantitative plant growth monitoring. (**i**) digital photographs of device (**ii**) Plot illustrating the Barley plant growth in real time [43]. (**b**) A Bluetooth (BLE) and real-

time monitoring system integrated with a PI-based plant drought stress sensor [102]. (**c**) Flexible sensors attached to leaf surfaces that integrate temperature and humidity detection [103]. (**d**) Integrated structure of wearable sensors equipped with four groups of volatile organic compound sensors, one leaf surface relative humidity sensor, one leaf temperature sensor and one ambient humidity sensor [44]. (**e**) Wearable plant sensing equipment integrated with temperature, humidity and spectral sensors for continuous monitoring of tomato stress status [104]. (**f**) Wearable sensor arrays attached to wheat leaves can detect the characteristics of wheat scab in situ [105]. (**g**) Wearable sensors for rapid, non-destructive and long-term monitoring of chlorophyll in plant leaves [106].

4.1. Physical Parameter Sensing

4.1.1. Growth and Deformation Monitoring

Plant stem and fruit growth involves continuous mechanical deformation, so attaching or wrapping flexible strain sensors onto the surface of plant organs provides a direct, non-invasive route to growth tracking. Early work demonstrated the feasibility of compliant conformal electronic patches for high-sensitivity monitoring of leaf micro-elongation through resistance changes [43]. Conductive ink and composite strain sensors have subsequently been used for real-time monitoring of stem growth and mechanical damage, with gauge factors of 64 and stretchability of 60% [47], and graphite/carbon-nanotube composite films (gauge factors 48–352, stretchability 150%) revealed that fruit growth in plants, such as eggplant, follows a rhythmic pattern of alternating rapid expansion and quiescence [48]. Structural and biomimetic designs further improved conformability and ease of attachment: tendril-inspired laser-induced graphene and pre-strained Eco-flex devices self-wrap around stems without adhesives by converting tensile deformation into bending [107], origami-inspired highly stretchable and breathable 3D sensors combine growth and microclimate monitoring [108], and paper-lock structures wrapped around stems enable low-cost, continuous radial growth measurement using the non-contact principle of an optical mouse [109]. Platform-level systems now integrate multiple functions on a single wearable device. Multifunctional stretchable sensors track leaf physiological parameters and microclimate over long periods [103]; PlantRing integrates strain and temperature-humidity sensing on a ring platform, offering a maximum tensile strain of 100%, season-long durability, and compatibility with most crops [110]; and Plant-Wear uses fiber Bragg grating sensors for simultaneous monitoring of growth strain and microclimate temperature/humidity [111]. Biointerface engineering has also improved plant compatibility and reduced interfacial abiotic stress, while dual-network crosslinked materials maintain high sensing sensitivity over wide temperature and humidity ranges [112]. Overall, growth monitoring has evolved from single-axis strain measurements to self-attaching, multimodal, season-long wearable platforms.

4.1.2. Water Status and Microclimate Monitoring

Leaf water status is commonly characterized by two complementary quantities: the internal water content within leaf tissues (i.e., leaf relative water content) and the external moisture at the leaf surface and its microenvironment (i.e., surface humidity and transpiration). Internal leaf water content is correlated with tissue water potential and cell turgor and thus serves as an indirect indicator of water deficit [113,114], whereas external leaf-surface moisture, including transpiration, reflects plant water status and responses to environmental stress. Wearable sensors targeting internal leaf water content or external leaf-surface moisture have therefore been widely developed. Freestanding Ni structure impedance sensors on polyimide substrates achieved stable leaf water-content monitoring, with signal stability maintained at wind speeds up to 2.00 m/s and excellent biocompatibility [115]. Self-adhesive, waterproof, and gas-permeable graphene electrodes enabled continuous water-status monitoring without external adhesives [116], and gra-

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dient porous electrode structures improved humidity-sensing response speed and sensitivity for real-time leaf surface humidity tracking [117]. For transpiration monitoring, graphene-oxide-based flexible sensors combined with PDMS-GO-SDS substrates accurately and continuously measured leaf surface temperature, humidity, and vapor pressure deficit [118]; covalent-organic-framework humidity films supported continuous transpiration monitoring for more than 15 days under different abiotic stresses [117,119]; laser-induced graphene/graphene-oxide capacitive humidity sensors achieved a sensitivity of 3215.25 pF/%RH [120]; and Ti/Au/PI/PET capacitive sensors enabled real-time drought-stress monitoring [102]. Beyond humidity, positive temperature coefficient thermistors wrapped around stems measured the spatial anisotropy of thermal transport caused by sap flow, enabling non-invasive continuous sap-flow monitoring [121], and nanoparticle-based conducting ink sensors positioned over single stomata tracked aperture opening and closing dynamics through resistance changes [122]. Together, these devices convert leaf and stem water status into continuous, field-deployable signals, although environmental cross-sensitivity remains a concern.

4.2. Chemical Parameter Sensing

4.2.1. Volatile Organic Compounds and Gas Monitoring

Volatile organic compounds (VOCs) released by plants are important chemical biomarkers that reflect physiological status [123]. VOC sensing strategies have diversified along complementary transduction routes. Electrochemical sensors, including flexible amperometric devices based on conducting polymers and platinum nanoparticles with micro gas collection chambers and hydrophobic gas-diffusion membranes, have achieved real-time methanol detection (0.5–500 ppm) on maize leaves [124] and conformal flexible electrochemical sensors have reached sub-ppm methanol detection on corn leaves [125]. Chemiresistive and radio-frequency approaches have enabled fingerprinting and wireless monitoring: gold-coated silver nanowire arrays with thiol ligands distinguish different disease stresses through VOC fingerprints [126]; all-MXene-printed RF resonators provide wireless, passive ethylene detection on fruit surfaces [127]; and wireless chemiresistive gas sensors detect stress-related α-pinene vapor at room temperature [128]. Colorimetric and printed-material strategies offer eye-readable and scalable alternatives. Extrusion-printed MOF colorimetric sensor arrays detect fungal disease VOCs [105]; eye-readable colorimetric arrays achieve detection limits of 5 ppm [129]; vapor-deposited conducting-polymer "electronic tattoos" (<1 μm) enable in situ O_3 monitoring on grape leaves [130]; and vapor-phase-printed polymer electrodes support long-term non-invasive physiological monitoring [131]. Ethylene has been a particularly active target, addressed by selective Cr_2O_3/SnO_2 bilayer structures [132] and by tattoo-style copper complex/SWCNT sensors that integrate ESP32 Wi-Fi transmission, IoT functionality, and temperature compensation [133]. Multimodal patches with stomatal-density-optimized placement on the abaxial leaf surface combine VOC, temperature, and humidity sensing [44], using ethylene-vinyl acetate copolymer (PEVA)/multi-walled carbon nanotube (MWCNT) composite material as the sensitive membrane can effectively monitor α-pinene vapor released from plants [128]. Collectively, VOC sensing is advancing toward array-based fingerprints, wireless operation, and IoT connectivity, but cross-species calibration and selectivity remain key challenges.

4.2.2. Pesticides, Phytohormones, Metabolites, Ions, and Pathogens

In addition to pesticide residues, this subsection covers phytohormones, metabolites, ions, and pathogens, which represent key chemical and biological targets for non-invasive plant health monitoring [134]. Pesticide residue detection is critical for agricultural product safety [135,136]. Enzyme-based flexible biosensors using organophosphorus hydrolase on laser-induced graphene electrodes provide selective real-time detection of methyl parathion [137], and microfluidic chips integrated with flexible electrochemical sensors enable smartphone-driven methyl parathion detection [138]. Screen-printed non-enzymatic sensors on degradable cellulose acetate substrates, attached directly to lettuce and tomato surfaces, detected carbendazim and paraquat with limits of detection of 54.9 and 19.8 nmol/L, respectively, within a linear range of 0.1–1.0 μmol/L [139], while laser-scribed graphene on paper provided a portable electrochemical platform for non-destructive paraquat detection on plant and fruit surfaces [140]. Fluorescence- and composite-based strategies include CdTe quantum dots embedded in PVA/agarose hydrogels for triazine pesticide detection [141] and ZIF@UCNP@PDA hydrogel patches for real-time pesticide monitoring [142], while flower-like origami paper biosensors detect pesticides in the aerosol phase [143]. Multi-analyte and sustainable platforms have also emerged: laser-induced graphene electrodes simultaneously monitored neonicotinoid insecticides, SA, and pH in rice guttation [144]; flexible electrochemical sensors detected ABA on tomato leaves [145]; cellulose-nanofiber substrates enabled biodegradable wearable sensors [146]; and sprayable AgNP/all-carbon nanostructure arrays provided scalable NO_2 detection [147]. For ions and metabolites, reverse iontophoresis has enabled non-invasive continuous glucose monitoring [148] and was first applied to in situ SA detection [149]; flexible electrochemical sensors have continuously monitored gallic acid [150]; carbon tape/MWCNT/Nafion electrodes quantified SA [151]; and AuNP-enhanced electrochemical immunosensors detected plant pathogens [152]. Overall, this body of work shows a clear trend toward multi-residue, field-deployable, and environmentally friendly pesticide sensors, with sensitivity and specificity increasingly controlled at the material level.

4.2.3. Optical and Optoelectronic Sensing

Optical and optoelectronic sensing provides contact-free or low-contact alternatives for non-invasive plant monitoring, and the information acquired can characterize plant stress status [151,153]. Capacitance-based approaches exploiting the difference between leaf mesophyll tissue and water provide a physiological parameter for monitoring internal leaf water content [154–156]. The contact electrification of liquid droplets impacting living plant leaves has also been investigated, providing a physical basis for self-powered plant sensing [157]. Hydrogel-electrolyte interfaces enabled non-invasive measurement of plant electrochemical potentials [158,159]. Transparent sensors based on nano-Ag films on PET substrates achieved high-precision growth monitoring (R^2 = 0.999) [160], and multimodal flexible systems based on $ZnIn_2S_4$ nanosheets detected light intensity and humidity simultaneously [161]. Miniaturized wearable reflectance meters have been developed for long-term in situ chlorophyll monitoring [106]. Morphable ionic gel electrodes extended non-invasive electrophysiological recording to hairy plant surfaces [162], and electrical impedance spectroscopy enabled long-term non-destructive monitoring of tomato nitrogen nutrition status, with prediction models established for leaf nitrogen content [163]. These methods complement electrochemical sensing by providing optical, electrical, and self-powered readouts that avoid direct tissue contact.

4.3. Multimodal Integrated Sensing

Non-invasive sensors acquire surface signals that are inherently indirect and environmentally sensitive, so a single surface parameter, such as leaf temperature, leaf surface humidity, or VOC concentration, cannot uniquely correspond to a specific plant physiological state and is readily susceptible to environmental interference. Consequently, multimodal integration has become a major design strategy [164]. By integrating multiple complementary sensing units on the same flexible platform and fusing multi-parameter data through machine learning, non-invasive sensors can achieve near-physiological diagnostic specificity despite lacking direct access to intracellular molecular measurements. In contrast, invasive sensors require less multimodal integration because a single channel can already provide molecular-level specific signals, explaining the marked difference in multimodal design density between the two technological routes.

Multifunctional stretchable sensors integrating strain, temperature, and humidity units on a single flexible substrate have enabled weeks-scale synchronized monitoring of leaf physiology and microclimate [103]. The Plant-Wear platform combines fiber Bragg grating growth-strain sensing with temperature and humidity sensors in a single system, attached to stems via flexible silicone clamps [111]. Semi-embedded flexible multifunctional sensors simultaneously monitor temperature, humidity, and light [165], and hybrid multifunctional physicochemical sensor suites combine multiple transduction mechanisms for continuous crop health monitoring [166]. Machine learning has become an integral component of multimodal systems: spectral-dominant soft wearable systems fuse spectral responses with temperature, humidity, and other parameters for long-term, early-stage diagnosis of plant stresses [104], while leaf-abaxial multimodal patches combining four groups of VOC sensors with leaf surface relative humidity, leaf temperature, and ambient humidity sensors enable quantitative disease detection as early as four days after virus inoculation through deep learning [44]. Optical-humidity fusion has also been demonstrated using $ZnIn_2S_4$ nanosheets [161]. These examples show that multimodal fusion, rather than any single parameter, is the key to approaching the diagnostic specificity of invasive molecular sensing.

4.4. Advantages and Limitations of Non-Invasive Sensing

Non-invasive sensing technologies have undergone explosive development between 2018 and 2025, covering a wide range of detection targets from macroscopic mechanical parameters (growth, deformation) to microscopic chemical signals (VOCs, ROS, ions). Their core advantages include: maintaining cuticle integrity and avoiding wound responses; good mechanical matching between flexible substrates and plant surfaces supporting weeks to months of continuous monitoring; and relatively simple fabrication processes (LIG, screen printing, inkjet printing) with scalability potential. However, non-invasive sensing faces a structural bottleneck in molecular information depth: the sensing interface located outside the cuticle cannot directly access intracellular transient biochemical signals, with detection limits typically at the μM level (2–3 orders of magnitude higher than the nM–pM level of invasive approaches). Furthermore, environmental noise (temperature drift, humidity cross-sensitivity, light variations) has a more significant impact on signal stability compared to implantable devices. Durability at the attachment interface under extreme weather or rapid plant growth conditions remains a concern; most non-invasive systems have so far been demonstrated at the laboratory or controlled-environment scale, and genuine multi-season field validation remains limited. Durability at the attachment interface, together with reliability validation from laboratory to field scale, remain the most prominent bottlenecks.

5. Comparison and Selection Decision of Plant Wearable Sensors

The preceding sections have reviewed representative works and performance characteristics of invasive (Section 3) and non-invasive (Section 4) plant wearable sensing technologies. This section provides a systematic head-to-head comparison, establishing a multi-dimensional comparison matrix and a technology selection framework to guide decision-making for different application scenarios.

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5.1. Multi-Dimensional Comparison Matrix

To systematically address the first core question posed in the Introduction—how invasive and non-invasive plant wearable sensors differ in signal quality, physiological disturbance, long-term stability, and field deployability—this section constructs a multi-dimensional comparison matrix (Table 3) based on the literature analysis in Sections 3 and 4. The matrix places invasive, minimally invasive, and non-invasive technologies within a unified comparison framework, covering six dimensions: signal characteristics, plant disturbance, long-term stability, manufacturing complexity, field deployability, and biosafety. Representative references are annotated at key performance indicators to ensure that every comparative conclusion can be traced back to the original studies.

Table 3. Multi-dimensional comparison matrix of plant wearable sensors (Note: detection limits, durations, and temporal resolutions are indicative ranges reported across heterogeneous analytes, species, tissues, and experimental conditions, not intrinsic limits of each category).

Comparison Item	Invasive	Minimally Invasive	Non-Invasive
	Signal characteristics		
Typical analytes	NO, H_2O_2, SA, ABA, IAA (intracellular) [46,56,72]	SA, glucose, Na^+, polyphenols (intercellular/vascular) [89,90]	VOCs, T/RH, transpiration, strain, pesticides (surface) [124,137]
Detection limit	nM–pM [46,72]	µM–nM [89,93]	µM [115,124]
Temporal resolution	Real-time (seconds)	Seconds to minutes	Seconds to minutes
Effective duration	several days ([73]: 48 h drift < 10%)	weeks ([63]: >14 d)	weeks–months ([119]: >15 d)
	Plant disturbance		
Tissue damage	Yes (puncture/injection) [46]	Mild (shallow microneedle) [89]	None [43]
Wound response	ROS burst, callus formation [45]	Negligible or reversible	None
Signal drift risk	High (biological barriers)	Medium	Low
	Fabrication & deployment		
Process complexity	High: nanomaterial synthesis + precision injection	Medium: MEMS/microfabrication	Medium–low: printing/LIG/coating
Field readiness	Low (requires specialized equipment)	Medium (field-usable)	High (batch deployable)
Biosafety	Uncertain	Relatively clear	Clear

Before presenting these comparisons, it should be emphasized that the values in Table 3 are reported ranges compiled from studies that differ in analyte, plant species, tissue, matrix, environmental conditions, and experimental design. They therefore represent indicative route-level trends rather than universal intrinsic performance limits.

Table 3 reveals a core regularity across the three technology categories: an inherent trade-off between signal depth and biological disturbance. Invasive sensors position their sensing interface at the physiological signal source (cytoplasm, chloroplasts, apoplast), achieving nM–pM sensitivity and second-level response times; however, wound responses triggered by tissue penetration (ROS bursts, cell wall lignification, callus formation) substantially constrain their long-term operational stability (typically 1–7 days) and require specialized injection or implantation equipment for field deployment. Non-invasive sensors, by fully preserving cuticle integrity, gain weeks-to-months of continuous monitoring capability and immediate on-plant deployment convenience, but the indirectness of surface signals confines detection limits to the μM level—2–3 orders of magnitude higher than invasive approaches. Minimally invasive technologies provide a compromise by limiting puncture depth (<200 μm) and electrode dimensions (1–100 μm), maintaining μM–nM sensitivity while reducing plant disturbance to an acceptable level, though the literature base for this route remains comparatively limited.

Notably, this trade-off is not solely determined by the physical position of the sensing interface but is also constrained by the biological characteristics of the plant itself. Cuticle thickness, which varies considerably among species (typically 0.1–10 μm) [61], together with stomatal density distribution and the presence of trichomes and wax layers on leaf surfaces, affects the interfacial adaptability of the same sensor type across different plant species. The comparisons presented in Table 2 should therefore be regarded as route-level generalizations rather than precise predictions for specific plant–sensor combinations.

5.2. Selection Decision Framework

After comparing the results, this section further proposes an application-oriented selection decision framework (Figure 3) to address the second core research question raised in the introduction—how to select the most suitable sensing technology for diverse application requirements. This framework adopts a three-layer progressive decision-making logic, breaking down the selection process into three interconnected judgment steps. Throughout this discussion, we distinguish three levels of evidence: (i) laboratory demonstrations, which validate working principles under controlled conditions; (ii) genuine field validation, which confirms long-term operation on real crops under field weather, deployment, and maintenance constraints; and (iii) technology readiness for commercialization, which additionally requires manufacturability, cost, reliability, calibration, power supply, wireless communication, and economic viability. Unless otherwise stated, "field deployable" and "commercialization potential" in this review refer to demonstrated feasibility rather than established, field-proven products.

Layer 1: Determine the technical category based on the biological hierarchy of target analytes. If the monitored targets are transient biochemical signals inside cells (such as ROS bursts, NO signals, and fluctuating concentrations of plant hormones), invasive nanosensors or implanted microelectrodes shall be prioritized. If the monitored targets are intermediate signals between cells and tissue surfaces (including vascular bundle ion concentrations and intercellular metabolites) with limited tolerance to tissue damage, minimally invasive microneedle arrays or ultra-thin microelectrodes represent more viable options. If the monitoring targets are macroscopic physiological parameters (growth rates, transpiration intensity, VOC emissions) or large-scale field deployment is required, non-invasive flexible patch sensors are the primary choice.

Layer 2: Evaluate long-term stability requirements according to deployment duration and scenario constraints. For short-term (several days) high-precision measurements in controlled laboratory environments, invasive solutions can fully leverage their superior sensitivity. For field or greenhouse scenarios requiring continuous monitoring spanning weeks to months, non-invasive solutions deliver greater practicality due to their long-term stability and near-zero maintenance demands. Minimally invasive solutions are applicable to medium-duration monitoring (1–2 weeks) where target analytes reside in superficial tissues.

Layer 3: Consider the techno-economic feasibility of large-scale deployment. Non-invasive sensors (especially those fabricated via LIG, screen printing and inkjet printing technologies) currently offer the most favorable cost and scalability profile, making them the most promising candidates for commercialization among the three routes. However, this potential remains conditional on further advances in manufacturing cost, long-term reliability, calibration, power supply, wireless communication, maintenance, and overall economic viability. Invasive sensors remain largely confined to laboratory research at present, owing to sophisticated nanomaterial fabrication procedures and precise implantation prerequisites. Minimally invasive sensors fall between the other two categories in terms of manufacturing complexity and deployment costs, and are currently transitioning from laboratory research to demonstration applications.

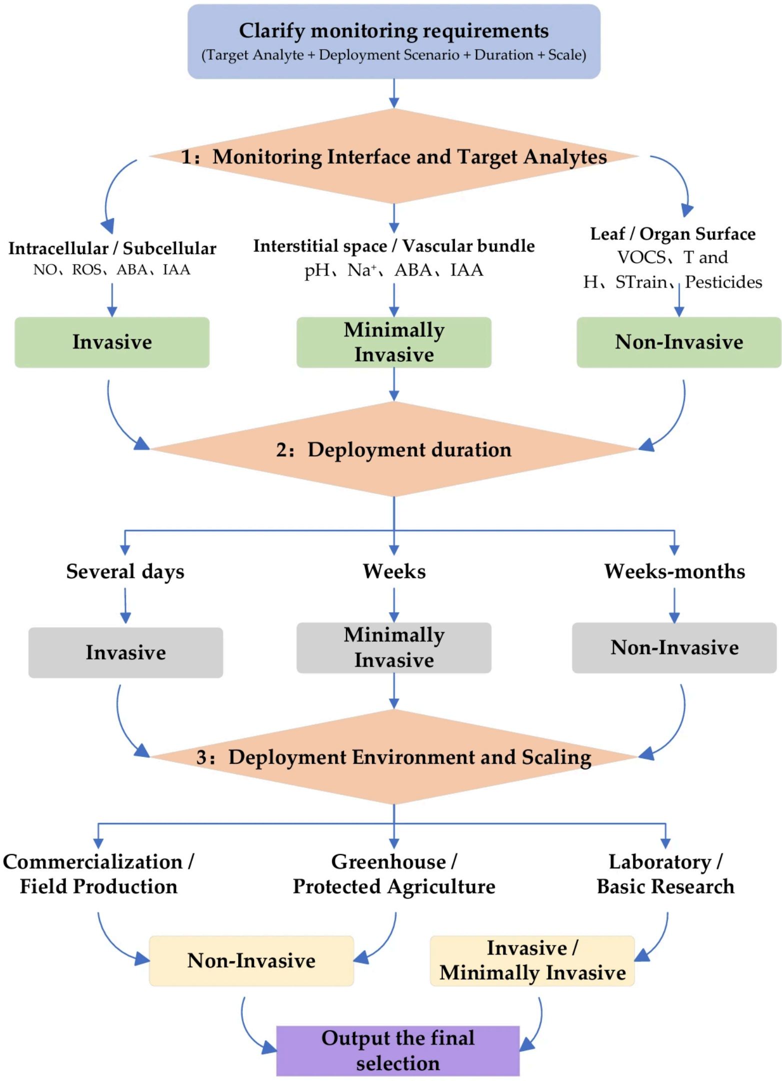

Figure 3. Selection Decision Framework Oriented to Application Scenarios.

It is important to emphasize that this decision framework delivers a priority ranking for technology selection rather than absolute rigid rules. In practical implementations, sensor performance is additionally constrained by factors, including target crop species, sensor-plant interface compatibility, and data acquisition and transmission infrastructure. At the system level, large-scale deployment will also require effective interconnection, traceability, and integration of sensing nodes within broader agricultural information networks [167]. Validation and adjustment of outputs generated by the framework are recommended for specific real-world scenarios. Furthermore, systematic studies conducting direct side-by-side comparisons of invasive, minimally invasive and non-invasive sensing modalities under identical experimental conditions are currently scarce. The cross-study comparability of parameters is hindered by discrepancies in experimental setups, plant species and data analytical workflows, a research gap that warrants further exploration in future work.

6. Conclusions

Plant wearable sensors have emerged as a key technological bridge linking plant physiological status to precision agriculture decision-making, undergoing rapid development from proof-of-concept demonstrations to multimodal integration over the past several years. This review systematically surveyed research progress in this field around the core dimension of the degree of intervention exerted on plants, establishing a three-tier classification framework encompassing invasive, minimally invasive, and non-invasive approaches. By synthesizing these representative studies, we conducted a head-to-head comparison of the three technology categories across six dimensions—signal characteristics, plant disturbance, long-term stability, manufacturing complexity, field deployability, and biosafety—revealing the core regularity underlying the field: an inherent tension between signal depth and biological disturbance, with no universally optimal solution applicable to all scenarios.

Within the invasive technological route, nanobionic sensors and implantable microelectrodes achieve molecular detection sensitivity at the nM–pM level with second-level response times, enabling real-time acquisition of key signaling molecules, such as NO, H_2O_2, and phytohormones at the cellular/subcellular scale, providing irreplaceable tools for early molecular diagnosis of plant stress. However, wound responses triggered by tissue penetration (ROS bursts, cell wall lignification, callus formation) lead to signal drift and limited sensor lifetime (several-day scale), and the long-term biocompatibility and ecological safety of nanomaterials remain inadequately assessed. Implantable OECTs and biofuel cells exhibit unique advantages in ion detection and self-powering, but device dimensions and power stability constrain their application scope. Minimally invasive technologies, through microneedle arrays and ultra-thin microelectrodes (1–100 μm), maintain μM–nM level detection capability while reducing tissue damage, representing a transitional solution between invasive and non-invasive extremes. Although the literature base for this route remains relatively limited, its "low-disturbance, medium-depth" positioning provides an important technological bridge between the two extreme approaches.

Non-invasive technologies, through surface-attached deployment, achieve weeks-to-months of continuous monitoring of multiple parameters, including plant growth, transpiration, VOC emissions, and pesticide residues, with fabrication processes (LIG, screen printing, inkjet printing) amenable to scaled production, and therefore currently represent the most promising route toward commercial application, subject to unresolved challenges in manufacturing cost, reliability, calibration, power supply, wireless communication, maintenance, and economic viability—currently the most promising route toward commercial application. To compensate for the ambiguity of single-parameter surface signals, non-invasive sensors widely adopt multimodal integration and machine learning-based data fusion strategies—a technical feature that corroborates the physical principle that "surface signal indirectness necessitates multi-parameter compensation."

Based on the above comparison, this review proposes a decision framework based on three-layer selection: first, the technology direction is determined according to the biological level of the target analyte; second, feasibility screening is performed based on deployment duration and environmental conditions; and finally, optimal selection is conducted according to scalability and cost constraints. This framework provides clear technology selection pathways for different application scenarios (laboratory mechanistic research, field-scale deployment, and closed-loop control in controlled environment agriculture).

It should be noted that systematic studies directly comparing the three technology categories under identical experimental conditions remain lacking, and cross-study parameter comparability is constrained by differences in experimental conditions and plant species. Future research should focus on three directions: first, establishing unified sensor performance evaluation standards and quantitative protocols for plant disturbance assessment, laying the foundation for cross-study comparisons; second, developing integrated sensing systems featuring biodegradability, self-powering, and wireless transmission to address energy supply and retrieval bottlenecks in long-term field deployment; and third, advancing the fusion of invasive–non-invasive hybrid sensing networks with plant digital twin models, enabling a leap from single-point measurements to canopy-level physiological state reconstruction. Controlled environment agriculture, with its controllable environment, high crop added value, and mature automation infrastructure, is poised to become the first deployment scenario transitioning plant wearable sensors from laboratory to large-scale application.

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