



Microneedle-based electrochemical sensors for in planta chemical sensing: From analytical principles to field deployment

Águeda Molinero-Fernández^{a,1}, Qianyu Wang^{b,1}, Maria Cuartero^{a,b,*}, Gaston A. Crespo^{a,b,**}

^a UCAM-SENS, Universidad Católica San Antonio de Murcia, UCAM HiTech, Avda. Andres Hernandez Ros 1, Murcia, 30107, Spain

^b Department of Chemistry, KTH Royal Institute of Technology, Teknikringen 30, Stockholm, SE-114 28, Sweden

ARTICLE INFO

Keywords:

Microneedle sensors
Electrochemical sensing
Plant bioanalysis
In planta monitoring
Precision agriculture

ABSTRACT

By 2050, the global population is projected to approach 10 billion, requiring substantial increases in crop productivity under growing land, water, and climate constraints. In this context, plant wearables have emerged as powerful AgriTech tools, highlighted by the inclusion of wearable plant sensors in the World Economic Forum's Top 10 Emerging Technologies report of 2023 and autonomous biochemical sensing in 2025. Among these technologies, microneedle (MN) electrochemical sensors provide minimally invasive access to plant biofluids and are rapidly becoming a promising platform for real-time chemical monitoring in living plants. In this review, we examine the key design requirements, analytical challenges, and applications of MN-based in planta sensors for monitoring nutrients, agrochemicals, phytohormones, growth precursors, and stress biomarkers. We first discuss the plant–MN interface, relating plant organs, biofluid composition, and tissue mechanics to MN design considerations. We then describe the principal MN architectures and electroanalytical techniques used to develop sensing platforms. Representative case studies illustrate how MN sensors can resolve the spatial and temporal dynamics of target analytes directly in plants, with emphasis on analytical performance under realistic or in vivo conditions. We further assess the main challenges limiting the translation of MN sensors from laboratory prototypes to autonomous systems suitable for field deployment. Finally, we outline opportunities arising from advances in flexible electronics, wireless communication, Internet-of-Things infrastructures, and artificial-intelligence-driven data analysis. Overall, this review provides an analytical framework for microneedle-based plant (bio)sensing and highlights their potential role in next-generation smart agriculture. We analyzed a collection of over 170 references (2016–2026) identified by database searches, pertinent keywords, and recognized contributions in this field.

1. Introduction

Global population growth, estimated to reach approx. 9.8 billion by 2050, is projected to exert unprecedented pressure on food systems [1]. Meeting this demand is expected to require a 70–100% increase in food production to ensure availability without compromising food security [2]. In addition to this challenge, climate change will intensify agricultural stress through rising temperatures, shifting rainfall patterns, and more frequent extreme weather events. Moreover, pest and disease control in many cropping systems still relies on calendar-based or visually triggered pesticide applications rather than on direct chemical evidence from plants. From an analytical chemistry perspective, these

pressures translate into the need for quantitative, plant-level measurements of nutrients, signaling molecules, stress markers, and agrochemical residues in real time. Such real-time in planta biochemical information would enable faster and more targeted decision-making, reducing both economic costs and off-target environmental impacts, while supporting sustainable precision agriculture strategies that rely on robust plant-level analytics [3,4].

It is worth mentioning that monitoring of these endogenous and exogenous analytes still depends largely on centralized laboratory analyses, which are time-consuming, and destructive methods that hinder timely corrective actions [5–7]. Moreover, because these methods capture only discrete data, they cannot track transient or long-distance

* Corresponding author. UCAM-SENS, Universidad Católica San Antonio de Murcia, UCAM HiTech, Avda. Andres Hernandez Ros 1, 30107, Murcia, Spain.

** Corresponding author. UCAM-SENS, Universidad Católica San Antonio de Murcia, UCAM HiTech, Avda. Andres Hernandez Ros 1, 30107, Murcia, Spain.

E-mail addresses: mariacb@kth.se (M. Cuartero), gacp@kth.se (G.A. Crespo).

¹ These authors contributed equally to this work.

dynamic events. Recent studies show that precision agriculture offers considerable economic and agronomic benefits [8]. For example, when combined with real-time, in situ monitoring, precision agriculture enables the optimized application of fertilizers, pesticides, and water, reducing input costs by 10–30% while improving productivity [9,10].

Rooted in data-driven management, modern precision agriculture increasingly relies on advanced analytical tools in which functional materials, miniaturized sensors, and IoT infrastructures converge to enable real-time crop sensing and decision-making. This transition is reflected in the recognition of wearable plant sensors in 2023 and autonomous biochemical sensing in 2025 in the World Economic Forum's Top 10 Emerging Technologies reports. Within this framework, the sensing component plays a pivotal role as the quality and specificity of the information collected ultimately determine the reliability of data analysis and automated decision-making. However, most sensing approaches still rely on soil measurements, visual inspection, or environmental variables. Although valuable, these approaches mainly describe the conditions surrounding the plant and do not reveal the biochemical changes occurring inside the plant. This limitation creates a clear need for sensors capable of direct, minimally invasive chemical monitoring in living plants [11–13].

In this context, microneedle (MN)-based sensors represent a new frontier, enabling minimally invasive, in situ access to plant physiology and integrating crop chemical information with digital platforms for processing and automated decision-making. Driven by these unique capabilities, research on MN sensors for plant monitoring has grown rapidly in recent years. As illustrated in Fig. 2, the field has experienced a significant evolution since 2017, progressing from early proof-of-concept bulk electrical and flow measurements to more advanced platforms capable of the specific determination of metabolites, hormones, and stress biomarkers [14–20]. This rapid expansion has also highlighted the need for robust frameworks that critically assess performance figures of merit, practical limitations, and overall reliability for continuous field deployment. Recent reviews have summarized complementary dimensions of plant microneedle technologies, including materials and fabrication methods, mechanical performance and engineering considerations, and applications in plant-health, crop-quality, and food-quality monitoring [14–20]. In contrast, the present review addresses a more specific and complementary question: how should MN-based electrochemical sensors be designed, analytically evaluated, and translated into reliable tools for direct in planta chemical sensing? Building on these contributions, the present review is structured according to a different conceptual framework, adopting an analytical rather than a primarily descriptive perspective. As outlined in Fig. 1, the review follows the analytical workflow required to generate reliable information from MN-based plant sensing in realistic conditions, spanning sensor design and plant interfacing, electrochemical transduction,

data interpretation, and eventual decision support within precision agriculture. Accordingly, particular emphasis is placed on the interconnection between MN architecture, plant tissue mechanics, target-dependent analytical requirements, and validation under realistic plant-matrix conditions. Although the review focuses on electrochemical transduction mechanisms, selected optical MN platforms are discussed when relevant electrochemical examples are unavailable, as models for future electrochemical translation.

Within this framework, we first discuss plant anatomical structures and their implications for MN design, including physical insertion, analytical performance, and monitoring requirements (e.g., continuous versus discrete measurements). Next, we discuss the detection mechanisms, design principles, and analytical performance most relevant to plant monitoring. Representative case studies enable a more detailed discussion of achievements in device design, materials, and analytical performance, while also revealing the factors that still limit progress toward higher technology readiness. Finally, we discuss emerging directions in device integration, multiplexed sensing, and field deployment that may help translate experimental prototypes into scalable solutions.

2. The plant–MN interface: from anatomy to physiology

Plant physiology and chemical composition define not only the targets to be measured but also the physical and analytical constraints that sensors must overcome. Different organs are associated with distinct functions, for example, roots with nutrient and water uptake, stems with long-distance transport, and leaves with photosynthesis and transpiration, which create organ-specific analytical environments. These organs also differ in tissue hardness, spatial organization and biofluid accessibility, meaning that MN insertion, stability, and sampling depth must be tailored to the anatomical context. Understanding these interconnections is therefore essential for a rational MN design.

2.1. Plant compartments as a starting point for MN design

From the perspective of MN sensing, plant anatomy is primarily relevant because it defines the penetration barrier, the depth of the target compartment, and the composition of the matrix contacting the sensing interface. The cuticle and epidermis represent the first mechanical barrier that MN sensors must overcome (Fig. 3a). Their thickness, surface architecture, and mechanical properties vary across species and organs, creating substantial heterogeneity in insertion requirements [34,35]. Plant tissues also exhibit mechanical behavior markedly different from that of mammalian skin. Reported compressive strengths of plant materials span several orders of magnitude, from 0.3 to >300 MPa [36], whereas mammalian skin has been reported to exhibit

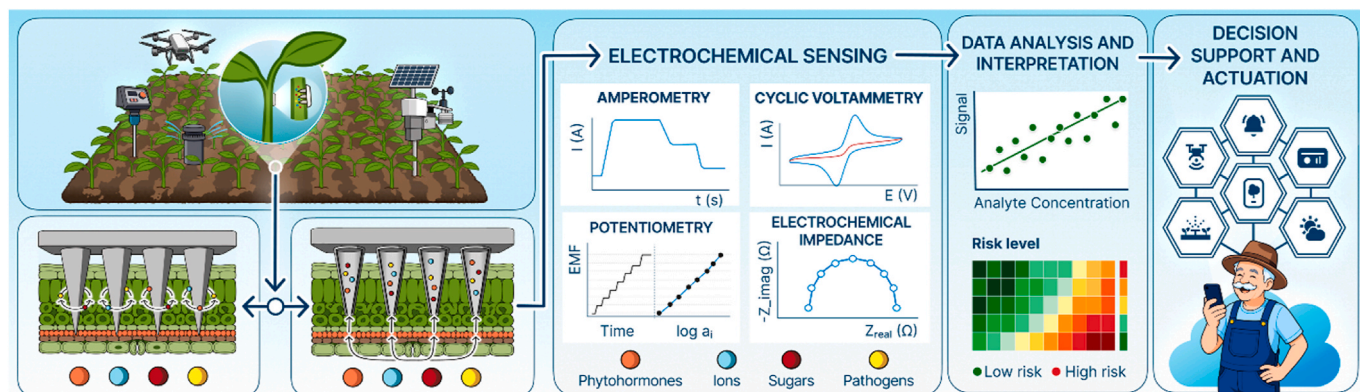


Fig. 1. Conceptual framework of the review. Analytical workflow of microneedle-based sensing in precision agriculture, from plant interfacing and electrochemical sensing to data analysis, interpretation, and decision support.

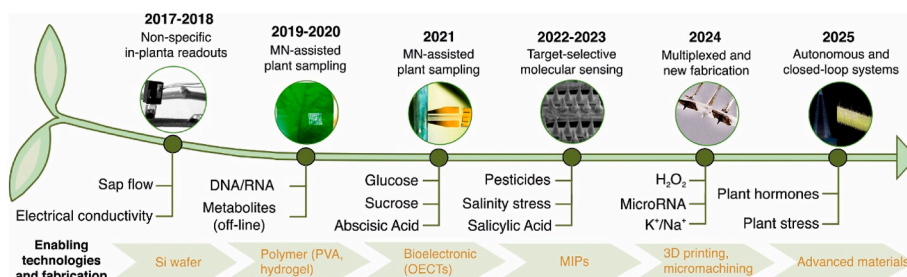


Fig. 2. Chronological overview of representative advances in microneedle-based plant sensing, highlighting key developments in targets, device configurations, and fabrication strategies from 2017 to 2025. Selected examples are adapted or reproduced from Refs. [21–33]. Permissions and license terms follow the corresponding original publications.

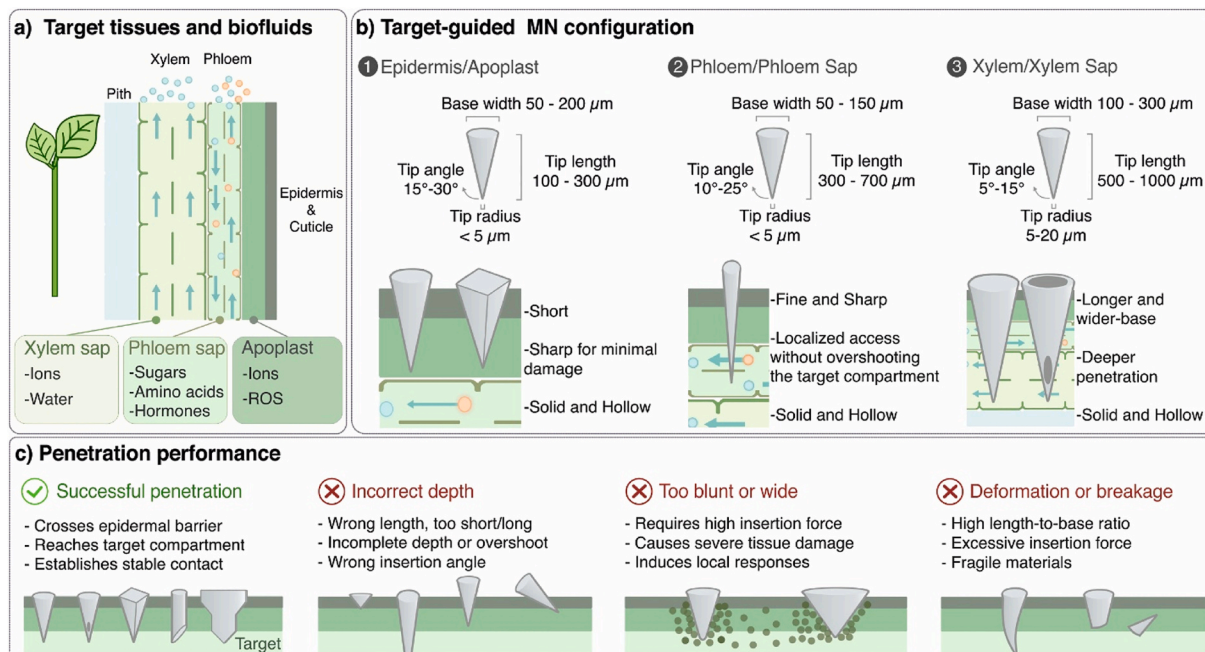


Fig. 3. a) Main stem tissues and biofluids accessible by microneedles (MNs). b) Target-specific MN geometries and dimensions for epidermis/apoplast, phloem, and xylem access. c) Successful penetration criteria and common insertion failure modes.

values of approximately 30 kPa under compression [37]. Consequently, the skin-based MN design criteria cannot be directly extrapolated to plant systems, and penetration performance must be independently validated for the intended plant species, organ, and target compartment, with MN geometry and insertion conditions optimized accordingly (as depicted in Fig. 3b and c and Section 3.1).

Depending on penetration depth, MNs can access the epidermal region and the apoplast, whereas deeper insertion is required to reach the xylem or phloem and access the corresponding vascular sap (Fig. 3). The apoplast comprises cell walls and intercellular spaces and contains water, inorganic ions, reactive oxygen species (ROS), and mobile phytohormones involved in local and rapid signaling [38,39]. Xylem sap is predominantly aqueous and enriched in dissolved macro- and micro-nutrient ions (e.g., K^+ , Ca^{2+} , NO_3^-), with a weakly acidic pH of approximately 5.0-6.5 [40]. In contrast, phloem sap is rich in sugars and also contains amino acids, hormones, proteins, and other metabolites, resulting in a more chemically complex and viscous matrix [7].

Together, these compartments offer complementary analytical windows but present contrasting composition, pH and biochemical complexity, which shape MN sensing performance. Therefore, the target tissue and biofluid should be defined before selecting the MN architecture. Near-surface apoplastic measurements favor short MNs and controlled insertion to minimize tissue perturbation, whereas vascular

measurements require deeper and more reproducible positioning. Xylem-oriented sensing must prioritize ion selectivity and stable operation in high-ionic-strength media, while phloem-oriented sensing places greater demands on antifouling strategies and the stability of biorecognition layers. Table 1 summarizes the most relevant access and matrix constraints for MN sensor design.

2.2. Plant biofluids as sources of chemical information through key analytes

Once the target compartment has been defined, the analyte class determines the sensitivity, selectivity, response time, and operational stability required from an MN sensor. Plant analytes are often classified according to their endogenous or exogenous origin [41]. However, this origin-based distinction does not fully capture the analytical demands associated with their measurement. We therefore organize the discussion into three analytical regimes according to typical abundance, temporal dynamics, and specificity requirements, beginning with the more abundant targets: (i) abundant ionic and metabolic targets, (ii) low-abundance and dynamic signaling analytes, and (iii) molecular and exogenous targets requiring highly specific detection. Table 2 provides an overview of the major analyte classes relevant to in planta MN-based sensing and their associated analytical requirements.

Table 1

Plant tissues, their accessible biofluids, and implications for MN sensor design [7,34,35,38–40].

Tissue	Location	Main function	Relevant physicochemical features	Biofluid accessible	Relevance of biofluid	Implications for MN sensor design
Epidermis	Outermost dermal layer	Protection against dehydration & pathogens	Waxy cuticle (0.2–10 μm), multilayered cells, mechanical heterogeneity	Apoplast (extracellular fluid)	Water content, inorganic ions, ROS, signaling molecules, nutrient status	Main penetration barrier
Xylem	Internal vascular tissue	Unidirectional water & mineral transport (root $\rightarrow$ shoot)	Dead conductive elements; acidic pH 5.0–6.5; high-ionic strength	Xylem sap	Higher percentage of sap volume: enriched in water and inorganic ions	Opportunity for water/nutrient monitoring
Phloem	Internal vascular tissue	Bidirectional transport of sugars & signaling molecules	Living sieve tubes; alkaline pH 7.3–8.5; metabolically complex (>300 compounds)	Phloem sap	Lower percentage of sap volume: sucrose, amino acids, hormones, proteins	Rich analytical target for systemic metabolism and stress signaling

Abbreviations: ROS: Reactive Oxygen Species.

Table 2

Relevant analytes for in planta monitoring and their associated analytical challenges for MN-based sensing.

Analyte class	Analytical priority	Primary analytical challenge	Additional analytical considerations
ROS/RNS (H_2O_2, NO) [42–46]	High	Detection of short-lived species under dynamic redox conditions	Low detection limits, rapid response and limited interference from other reactive species
Phytohormones (IAA, ABA, SA) [47–51]	High	Trace-level detection (nM– μM) in chemically complex plant matrices	Specificity and long-term stability of biorecognition layers
Nutrient ions (K^+, Na^+, Ca^{2+}, NO_3^-) [14, 52–54], and pH [55–59]	High	Ion selectivity in high-ionic-strength plant sap	Long-term stability and temperature compensation
Pathogens/pathogen markers (DNA/RNA, proteins, toxins) [60–70]	Medium-High	High specificity (i.e., strain-level discrimination) and sub-pM detection limits	Matrix interference, target extraction efficiency, and integration of amplification or immunorecognition steps
Sugars (sucrose, glucose) [29, 71–74]	Medium	Selective biorecognition in complex plant matrices	Long-term stability of biorecognition layers, and redox mediators.
Pesticides [23,75]	Medium-Low	Trace-level detection (nM–pM) in complex plant matrices	Heterogeneous tissue distribution

2.2.1. Ionic targets and primary metabolites

Among the more abundant plant constituents are proteins (e.g., aquaporins), enzymes (e.g., Rubisco), lipids, primary metabolites such as sugars, amino acids, and organic acids, and nutrient ions such as K^+ , Na^+ , Ca^{2+} , and NO_3^- . For MN-based sensing, current interest has focused primarily on nutrient ions, pH, and soluble sugars [76,77]. Ions such as K^+ , Na^+ , Ca^{2+} , and NO_3^- , together with pH, provide direct information on plant ionic and nutritional status. Because these targets are generally present at comparatively high levels (e.g., μM - mM range), the main analytical challenge is generally not achieving very low detection limits but maintaining selectivity and operational stability in complex plant sap. Ion and pH monitoring must address interference from coexisting ions, long-term signal drift, and temperature-dependent responses [14].

Soluble sugars such as sucrose and glucose are also relatively abundant (mM), particularly in phloem sap [7]. Nevertheless, their measurement remains challenging because sugar-rich biofluids are viscous and chemically complex [29,71–74]. Reliable sensing therefore requires

selective and stable recognition layers, resistance to surface fouling, and, for enzymatic electrochemical approaches, suitable redox mediators.

2.2.2. Low-abundance and dynamic signaling analytes

Phytohormones and reactive oxygen and nitrogen species are small molecules that constitute a more analytically demanding regime characterized by lower concentrations and rapid temporal variations. Phytohormones such as indole-3-acetic acid (IAA), abscisic acid (ABA), salicylic acid (SA), cytokinins, and gibberellins generally occur at nM– μM levels and can fluctuate rapidly during plant development and stress responses [78,79]. Their monitoring therefore requires sensitive and fast-response detection, together with selective and stable recognition layers capable of operating in chemically complex and potentially fouling plant matrices.

Reactive oxygen and nitrogen species, including H_2O_2 and NO, are short-lived and frequently electroactive signaling molecules involved in rapid stress responses [80]. Given their transient nature, MN sensors targeting these species should combine low detection limits and high temporal resolution with limited cross-reactivity toward coexisting electroactive compounds. In some cases, continuous monitoring of analyte trends may be informative even without accurate absolute quantification, provided that the sensor reliably captures their temporal evolution.

2.2.3. Exogenous targets: pathogen-associated biomarkers and pesticide residues

The main exogenous targets considered for MN-based sensing are pathogen-associated biomarkers and pesticide residues. Direct pathogen identification may rely on DNA/RNA, proteins, or toxins and requires high molecular specificity, efficient target extraction, and, in many cases, the integration of amplification or immunorecognition steps within the MN workflow [81,82]. Early detection of these biomarkers may enable timely intervention before substantial crop damage occurs. The primary analytical challenge lies in achieving high specificity (i.e., strain-level discrimination) and sub-pM detection limits in complex plant matrices. In practice, meeting these requirements demands careful consideration of matrix interference, target extraction efficiency, and the integration of amplification or immunorecognition steps directly within the MN architecture. Because infection management often relies on pesticides, their residues represent additional exogenous targets that may persist at trace concentrations and distribute heterogeneously across plant compartments, making sampling depth critical for MN-based detection [83]. Reliable MN-based detection therefore depends not only on sufficient sensitivity and chemical selectivity, but also on the appropriate selection of the sampled tissue and insertion depth.

Each of these analyte classes presents distinct analytical challenges for MN-based sensing, as summarized in Table 2. In addition to their main analytical requirements, the table includes an author-defined qualitative priority for monitoring. This prioritization considers: i) the agronomic relevance of each analyte, particularly its potential for early stress detection and actionable intervention, ii) its analytical difficulty,

including sensitivity, selectivity, temporal resolution, and matrix compatibility, iii) the availability of alternative non-invasive monitoring methods, and iv) the current number of reported MN-based studies. Based on this assessment, ROS/RNS, phytohormones, and nutrient ions and pH were assigned high priority, although for different reasons. ROS/RNS and phytohormones are associated with early and rapidly evolving stress responses, making sensitivity and temporal resolution particularly important. In contrast, nutrient ions and pH provide directly actionable information for crop management, with the main analytical challenges related to long-term stability, ion selectivity, signal drift, and temperature-dependent responses.

Pathogen-associated biomarkers were assigned medium-high priority because of their major agronomic impact and the value of early diagnosis, although their detection requires high molecular specificity and often involves extraction, amplification, or immunorecognition steps. Sugars were classified as medium priority because they are abundant and physiologically informative, but their continuous monitoring is limited by matrix viscosity, fouling, and the long-term stability of recognition layers. Pesticide residues were assigned medium-low priority because alternative residue-monitoring methods are available and their heterogeneous distribution across plant tissues complicates representative in planta sampling.

2.3. Analytical strategies and future directions for plant biofluids analysis

Although chemical information is essential for decision-making, plant monitoring still relies largely on visual inspection and environmental sensors that measure soil and microclimatic variables (e.g., relative humidity and air temperature), which cannot capture the biochemical status within plant tissues [75]. This disconnect between external monitoring and internal plant chemistry leaves a critical measurement gap at the biofluid level, causing crop management decisions to remain largely experience-driven rather than data-driven [84]. To address this limitation, recent research has focused on three main strategies for probing internal plant biofluids: (i) destructive laboratory-based extraction and chemical analysis, (ii) genetically encoded and optical nanosensors for in vivo molecular measurements, and (iii) remote imaging and spectral techniques for large-scale crop assessment. However, none of these approaches simultaneously offers high chemical specificity, real-time monitoring capabilities, and compatibility with field deployment. As a result, there remains a need for sensing technologies capable of directly accessing plant biofluids while providing continuous, minimally invasive, and field-deployable chemical measurements.

2.3.1. Conventional extraction-based analytical methods

Traditional workflows based on sample collection, freezing, homogenization, chemical extraction, and central laboratory analysis, remain the gold standard for accuracy but are inherently destructive and discontinuous [85–87]. They disrupt endogenous signaling, fail to capture transient biochemical dynamics, and introduce delays of several days between stress onset and its confirmation.

2.3.2. Genetically encoded and optical nanosensors

Advances in synthetic biology and nanotechnology have enabled the development of genetically encoded and optical nanosensors as new tools for in planta monitoring. Genetically encoded optical nanosensors are typically composed of two components: a binding protein with high specificity for the target molecule (e.g., bacterial periplasmic binding protein), and a fluorescent protein reporter integrated by genetic coding (e.g., the Förster resonance energy transfer (FRET) pair) [88,89]. In parallel, synthetic optical nanosensors exploit photoactive nanomaterials smaller than 100 nm to facilitate interactions at plant interfaces. While both strategies have been demonstrated to work in controlled environments, their broader adoption is hindered by uncertainties in nanosensor uptake and distribution within plant tissues, as

well as concerns regarding nanotoxicity, regulatory acceptance and food-chain exposure [1,14]. The potential entry of nanomaterial-treated plant products into the food chain raises safety and societal concerns that demand comprehensive toxicological assessment before field implementation. High costs and reliance on specialized optical instrumentation further limit their suitability for field deployment.

2.3.3. Remote imaging and spectroscopic approaches

Advances in imaging and spectroscopic technologies have enabled the development of remote, non-contact approaches for plant monitoring [90,91]. Techniques such as thermal, hyperspectral, and fluorescence imaging support large-scale phenotyping and provide valuable structural and physiological information at the canopy level. However, their ability to access molecular-level chemical information remains limited. Furthermore, field deployment is challenged by variable illumination conditions and canopy heterogeneity, which complicate optical signal interpretation and reduce analytical sensitivity and specificity. Other advanced analytical techniques, including positron emission tomography (PET) and X-ray fluorescence (XRF), can provide higher spatial and chemical resolution. However, their reliance on specialized instrumentation, high operational costs, and limited portability restrict their applicability for routine field monitoring [8,92].

Although these approaches have significantly expanded our ability to assess plant physiological status, none currently combines high chemical specificity, continuous monitoring capability, and practical field deployment. MN-based sensors offer a promising alternative by providing minimally invasive, real-time access to plant biofluids while remaining compatible with low-power wearable electronics for on-plant measurements. Originally developed for biomedical applications such as minimally invasive glucose monitoring [93–98], MN technologies are increasingly being adapted for agricultural systems. Nevertheless, their translation to in planta sensing introduces unique analytical challenges, including matrix complexity, biofouling, recalibration requirements, traceability, and long-term operational stability. Despite these challenges, the rapid growth of the field highlights the recognition of MN platforms as one of the most direct and promising routes toward continuous chemical monitoring in living plants. The following sections therefore focus on the design principles, analytical considerations, and current state of the art of MN-based plant sensors.

3. Microneedle sensors: analytical design principles and technological progress

In planta MN sensors should be conceived as integrated analytical devices that couple tissue access with signal generation and interpretation. This section outlines the design logic underlying these systems: the target biofluid defines the required access route, the MN configuration and geometry determine whether that compartment can be reached with limited damage, and the electrochemical readout establishes whether the resulting signal can be interpreted as a concentration, a temporal trend, or a physiological response.

3.1. Microneedle architecture and fabrication: implications for plant interfacing, sampling, and sensing

Plant MNs operate in mechanically heterogeneous tissues whose accessibility is governed by the cuticle, epidermis, cell walls, turgor pressure and vascular organization [34,99]. The composition and depth of these barriers are organ-dependent, meaning that MN insertion into a leaf or stem may require different geometries because of differences in mechanical rigidity, hydration state and vascular depth. For this reason, it is recommended that the target fluid, organ, and plant species are defined before selecting the MN architecture. Shorter MNs are more suitable for near-surface epidermal interrogation, whereas longer MNs are required to reach deeper vascular tissues and access sap. This distinction becomes particularly important for sap-oriented

measurements, where the type of sap being accessed is one of the first analytical variables to define. A schematic overview of the tissue-access design space for in planta MN sensing is shown in Fig. 3, linking target biofluids with suitable MN geometries and penetration outcomes.

For the MN to reach the intended compartment, parameters beyond needle length must be considered. Tip sharpness (tip angles $< 20\text{--}30^\circ$) and base width jointly govern the minimum force required for successful penetration: a smaller tip radius concentrates stress at the insertion point, lowering the penetration threshold, while a narrower base minimizes the wound cross-section, reducing both mechanical trauma and the extent of the local tissue response [100–102]. The geometric characteristics of MNs are inherently interdependent, collectively dictating insertion mechanics, tissue disruption patterns, and ultimately the identity and composition of the biofluid sampled at the sensing interface.

A further critical consideration is the method by which the MN is inserted into the tissue. The insertion angle determines the effective penetration depth of the sensing element, which may differ substantially from the nominal MN length. Oblique insertion reduces the depth reached by the active sensing region, whereas excessive insertion force or an inappropriate trajectory can lead to tissue deformation, sensor fracture, or penetration into unintended tissue compartments. To improve insertion reproducibility, applicator devices (widely employed in transdermal MN sensing and drug-delivery systems) enable precise control over insertion angle, velocity, and force. Such devices minimize operator-dependent variability and promote more consistent access to the targeted tissue and biofluid compartment [102].

A key architectural decision in MN design is the choice between solid and hollow configurations. Solid MNs are continuous structures without internal microchannels. This geometry offers greater mechanical resistance to bending, buckling, and fracture. For this reason, solid MNs are particularly attractive when reliable penetration is the primary requirement [17]. Depending on their composition, solid MNs may support direct sensing at the external surface or tip, or enable plant-fluid uptake through porous, absorbent, or hydrogel-based matrices. By contrast, hollow MNs incorporate an internal microchannel that can serve either as a conduit for direct plant biofluid extraction or as a protected compartment for integrating the sensing element within the needle body, depending on the analytical strategy. This functionality, however, comes at the expense of mechanical robustness: the presence of the lumen reduces the effective load-bearing cross-section of the needle, requiring tighter control of wall thickness, channel diameter, and tip geometry to avoid fracture or buckling during insertion [27,103,104]. Material selection and fabrication strategy must therefore be adapted to the selected architecture.

MNs can be fabricated from a range of materials, including metals, polymers, and silicon, each offering distinct trade-offs between mechanical robustness, biocompatibility, cost, and fabrication scalability [17]. Metallic MNs, typically composed of stainless steel or titanium, offer high mechanical resistance to fracture, making them well-suited to the high penetration forces required in plant tissues [17,101]. Their dimensional precision can be achieved via laser micromachining or micro hot embossing, and their durability allows repeated use [17]. However, metallic architectures involve complex and costly fabrication processes, and the sensing element must be incorporated via external surface modification, where it remains fully exposed to mechanical abrasion and chemical fouling during insertion. Among the available alternatives, polymer-based MNs are widely adopted, owing to their lower cost, ease of mold-based fabrication, and inherent biocompatibility. Materials such as PVA, silk fibroin, PDMS, PLGA, or SU-8 can be shaped into complex geometries via UV or thermal curing and can readily accommodate the integration of sensing layers during fabrication [17]. Their flexibility also enables better conformal contact with irregular plant surfaces. The main limitation is their reduced mechanical resistance compared with metals: softer polymers risk buckling or fracture in hard plant tissues such as lignified stems or thick cuticles, and

prolonged exposure to high humidity, UV radiation, and temperature fluctuations can cause swelling or degradation of the polymeric matrix [17,99,102]. Silicon offers high-dimensional precision through photolithography or deep reactive ion etching (DRIE), but its brittleness and cleanroom-dependent fabrication limit its scalability for field-oriented plant applications [17].

From a manufacturing perspective, solid MNs are generally simpler to fabricate because they require only the definition of the external needle geometry. They can be produced by micromachining, laser cutting, molding, or 3D printing, depending on the selected material and resolution requirements [17]. Among these approaches, 3D printing is particularly attractive for solid MN fabrication because it enables rapid prototyping, iterative optimization of needle height, base width, tip angle, and array layout without dedicated molds or cleanroom facilities [104,105]. Fused deposition modelling (FDM), stereolithography (SLA) and digital light processing (DLP) are accessible and scalable, but their limited resolution can produce blunter tips and wider insertion profiles, compromising penetration efficiency in mechanically resistant plant tissues [106,107].

Across 3D printing modalities, the range of compatible materials also remains narrower than that available through conventional mold-based fabrication, restricting the selection of mechanically robust, biocompatible, and chemically functionalizable substrates, as well as the integration of conductive coatings or sensing elements [106]. Higher-resolution approaches, such as two-photon polymerization, can generate sharper and more complex MN geometries, but their low throughput and high cost currently limit their use to proof-of-concept studies. For hollow MNs, fabrication is more demanding because the process must define not only the external needle geometry but also a continuous internal microchannel while preserving sufficient wall thickness.

Silicon-based hollow MNs are commonly produced by DRIE, whereas polymeric hollow architectures generally rely on sacrificial templating, multi-step molding, or high-resolution additive manufacturing [108]. Compared with solid MNs, these approaches impose stricter geometric constraints because the external needle profile, lumen diameter, wall thickness, and tip opening must be controlled simultaneously. In practice, maintaining channel continuity along the full needle length while avoiding clogging, tip blunting, or mechanical failure remains particularly challenging at small tip diameters.

Beyond fabrication and mechanical considerations, MN architecture also shapes the plant–MN analytical interface by determining how plant biofluids are accessed and how sampling and sensing are performed. In solid MNs, the external surface or tip may act either as a direct sensing interface or as a fluid-collecting matrix. For direct in situ sensing, conductive or transducing layers, selective membranes or bio-recognition elements, and, when required, protective coatings are sequentially deposited on the MN. After insertion, analyte transport through these functional layers is predominantly diffusion-controlled, followed by direct electrocatalysis or target recognition through ion partitioning, enzymatic conversion, or affinity binding. Accordingly, layer thickness, porosity, and hydration influence sensitivity and response time [28,109–111]. Because the coatings are directly exposed, they are susceptible to insertion-induced abrasion and fouling by sap macromolecules and phenolic compounds, while their adhesion and insertion resilience are rarely quantified. More robust attachment strategies, such as plasma-initiated covalent anchoring demonstrated for conventional ion-selective electrodes, could improve coating stability; however, their applicability to plant MNs remains unexplored, and additional protective or anchoring layers may increase mass-transfer resistance and slow the response [28,109,112]. Alternatively, porous, absorbent, or hydrogel-based solid MNs can collect plant fluid by imbibition or swelling for subsequent analysis [24,26]. Hydrogel matrices may also enable analyte enrichment: in dermal interstitial fluid (ISF), negatively charged hydrogel MNs have enabled the selective enrichment of positively charged metabolites [113]. Adapting this

strategy to plant biofluids could facilitate the preconcentration of low-abundance analytes, although this remains to be demonstrated in plants. In hollow MNs, the internal lumen constitutes a configurable fluidic and analytical compartment. Depending on the design, it may transfer sap to an external collector or detector [27,114], house a discrete protected sensing element [115], contain a functional sensing phase, or connect the insertion site to an integrated microfluidic sensing pathway [116]. Each configuration imposes different requirements for biofluid–sensor contact. For internal sensing, the incoming biofluid must wet the active phase; the position of this phase determines the analyte-transport distance, whereas its attachment to the lumen wall influences mechanical stability. Recessing the sensing region away from the tip protects it from insertion-induced abrasion but may increase the response time. When the lumen contains the sensing material, sufficient fluid entry and hydration of the active phase become more important than recovering a measurable bulk sample.

Apart from the structural challenges associated with hollow MN fabrication, a critical yet largely overlooked design variable, especially for in planta applications, is the physicochemical modification of the lumen surface. When the lumen is used for sampling, passive fluid uptake may be driven by capillarity or wicking. If these forces are insufficient, an absorbent collector or an imposed pressure gradient, such as external suction, may be required, adding auxiliary components and pressure-control requirements [27,117–119]. Lumen diameter and length, tip-opening geometry, surface wettability, sap viscosity, and sealing at the plant–MN interface therefore jointly determine the filling rate and recovered volume. Hydrophilic treatments can promote wetting and capillary filling and have been demonstrated in transdermal hollow MN systems [120,121], but remain largely unexplored in plant-oriented devices. Channel clogging is another important limitation: proteins and polysaccharides may adsorb onto internal surfaces or obstruct narrow channels, phenolic species may passivate sensing layers, and insertion-generated cellular debris may block the tip opening. Lumen geometry and chemistry should therefore be co-designed for the intended function (i.e., sampling, internal sensing, or both) while balancing fluid uptake, compatibility with the sensing or absorbent material, fouling resistance, and response time.

3.2. Detection principles

The detection principle ultimately determines whether a plant MN sensor can produce a measurable signal from the target biofluid. Its selection must consider not only the analyte class and concentration range, but also the physicochemical constraints of the plant matrix, such as high ionic strength, variable pH, and the presence of electroactive interferents. Optical readouts for plant sensing have been described elsewhere [122], covering fluorescent/FRET, plasmonic, and fiber-optic approaches. However, their translation into MN platforms remains limited and generally unsuitable for field deployment due to bulky optical instrumentation and the need for controlled illumination. In contrast, electrochemical transduction offers high sensitivity, low power consumption, compact instrumentation, and label-free operation, making it particularly compatible with miniaturized MN platforms. In practice, electrochemical MN systems primarily rely on three detection modes: voltammetric, potentiometric, and impedance-based approaches. A brief introduction to each detection principle and its plant-specific analytical constraints is provided in the following subsections.

3.2.1. Potentiometric methods

Potentiometric transduction measures changes in electrode potential under zero-current conditions, providing a simple and energy-efficient sensing strategy. By integrating ion-selective membranes (ISMs), MN potentiometric sensors achieve high ionic selectivity with minimal power requirements and simple readout electronics, attributes that are particularly well-suited for miniaturized platforms for continuous in

planta measurements. As a result, potentiometric transduction is particularly attractive for the monitoring of charged species in planta, where selective and minimally invasive operation is required. As illustrated by the examples compiled in Table 3, currently reported MN sensors have mainly targeted monovalent cations, including K^+ , Na^+ , and H^+ , driven by the availability of selective ionophores and their more favorable Nernstian sensitivity (~ 59 mV/dec) [14,28]. Beyond these, potentiometric MN sensors could be extended to multivalent cations such as Mg^{2+} , as recently demonstrated, as well as agronomically relevant anions such as NO_3^- and $H_2PO_4^-$ [123]. Notably, practical field deployment must also account for temperature-dependent changes in the Nernst response and the distinction between ionic activity and absolute concentration [14].

3.2.2. Voltammetric and amperometric methods

Both amperometric and voltammetric techniques rely on current–potential relationships, and their selection depends mainly on the target concentration range and the required analytical discrimination. Amperometric methods, which operate at a fixed potential, are particularly attractive for continuous monitoring and couple naturally to oxidase-based biosensing schemes, where the enzymatic reaction generates electroactive products such as H_2O_2 that can be directly quantified [95,128]. As reflected in Table 4, current MN implementations based on these methods have mainly targeted those species (i.e., H_2O_2 and glucose).

By contrast, voltammetric methods are more attractive when additional analytical discrimination or higher sensitivity is required. Among voltammetric techniques, cyclic voltammetry (CV) is primarily employed for sensor development and characterization, whereas pulse techniques such as differential pulse voltammetry (DPV) and square wave voltammetry (SWV) are better suited for quantitative *in planta* measurements. DPV can achieve nanomolar-to-picomolar detection limits, making it exceptionally qualified for tracking low-abundance signaling molecules like phytohormones (Table 4). When rapid response times are paramount, SWV offers a compelling alternative. However, deploying these pulse techniques within complex plant matrices requires addressing critical analytical challenges, including electrode biofouling and interference from endogenous electroactive coexisting species. These phenomena can compromise selectivity, ultimately undermining the reliability of quantification over extended in planta monitoring periods (see Section 5.1).

3.2.3. Impedimetric methods

Electrochemical impedance spectroscopy (EIS) probes the frequency-dependent electrical response of an electrode–electrolyte interface, providing critical insights into resistive and capacitive components without requiring electroactive analytes. By employing multi-frequency AC perturbations (typically 0.1 Hz–100 kHz), EIS characterizes the plant tissue–electrode interface through complex impedance ($Z' + jZ''$), which is conventionally interpreted using equivalent-circuit models. In the context of MN sensors, EIS has emerged as a powerful tool to interrogate cellular structure, water content, and overall physiological status. For instance, shifts in tissue impedance serve as a reliable proxy for plant health, enabling the early, non-destructive detection of agronomic stressors such as salt stress, pathogen infection, and fruit ripening [124, 134,135]. Notably, drought-induced lipid peroxidation, which alters cell membrane integrity, is directly reflected in changes to the Nyquist semicircle radius and Bode-frequency shifts. These impedance-derived parameters facilitate the assessment of stress tolerance within precision agriculture workflows. However, the structural complexity of plant tissues, where cell walls, membranes, and heterogeneous biofluids contribute simultaneously to the signal, remains a challenge, making it difficult to deconvolute specific biological processes or achieve absolute quantitative measurements.

Table 3

Microneedle sensors for bioelectrical signals and ion detection.

Analytes	Architecture	Transduction	Analytical features	Validation level	Deployment setting	Applicability details	ref
Plant electrophysiology (Action potentials)	Solid MN array	EIS	Amplitude = 11.7 ± 0.7 mV; SNR = 20.5 ± 5.5 dB	In planta without validation	Laboratory	Stress-response classification	[31]
Plant impedance	Solid MN array	EIS	Frequency range: 10 Hz–100 kHz; average relative noise: 3.83% (impedance), 7.61% (phase)	In planta with field deployment; not independently validated	Growth chamber and greenhouse	Long-term monitoring: 13 d in a growth chamber and 7 d in a greenhouse	[124]
pH	Solid MN array	Potentiometry	LRR: pH 4–8; Sensitivity: -59.9 ± 1.5 mV pH ⁻¹ ; Response time: 50s	In planta validated with pH meter	Laboratory	Continuous monitoring for 2 d	[125]
pH	Hollow MN array	Potentiometry	LRR: 5–8; Sensitivity: -71.0 mV pH ⁻¹	In planta validated with pH-meter	Laboratory	Discrete measurements; No continuous monitoring.	[27]
Na ⁺	Solid MN	Potentiometry	LRR: 10^{-2} – 10^{-5} M; Slope: 56.55 ± 0.25 mV dec ⁻¹ ; LOD: 1.94×10^{-6} M; Response time < 10s	In planta validated with ICP-OES	Laboratory	Continuous monitoring for 3 h	[109]
K ⁺ and Na ⁺	Solid MN	Potentiometry	Slope: ~ 55 – 57 mV dec ⁻¹ ; LRR: 10^{-1} – 10^{-5} M (Na ⁺), 10^{-1} – 10^{-4} M (K ⁺); LOD: $\sim 2.9 \times 10^{-5}$ (M) K ⁺ , $\sim 7.5 \times 10^{-6}$ M (Na ⁺); Response time: <5s K ⁺ and Na ⁺	In planta validated against IC	Laboratory	24 h monitoring	[28]
K ⁺	Solid MN	Potentiometry	LRR: 10^{-4} – 10^{-1} M; Slope: 59.3 ± 0.35 mV dec ⁻¹ ; LOD: 3.5×10^{-6} M; Response time: 15 ± 3 s; log K ^{pot} _{K,Na} = -0.2	In planta validated against IC	Laboratory	Continuous monitoring for 60 min of salt-induced K ⁺ loss in rice	[126]
Mg ²⁺	Solid MN	Potentiometry	LRR: 10^{-5} – 10^{-1} M; Slope: 29.00 ± 0.20 mV dec ⁻¹ ; LOD: $\sim 1.1 \times 10^{-7}$ M; Drift: ~ 0.3 mV h ⁻¹	In planta; dynamic trends compared with ICP-OES	Laboratory	>40 h xylem monitoring; first 4–8 h excluded; absolute quantification not validated	[123]
Plant impedance	Solid MN	EIS	Proof-of-concept, no quantitative analytical performance reported.	In planta without validation	Laboratory	Diurnal monitoring	[127]
Sap flow	Solid MN thermal probe	Modified heat dissipation method (Granier)	Pipe calibration: Range 0–4 mm s ⁻¹ , RMSE = 0.115 mm s ⁻¹ ; Xylem calibration: Range 0–3.07 mm s ⁻¹ , RMSE = 0.128 mm s ⁻¹	In planta without validation	Laboratory	Stress-response classification	[21]

Abbreviations: EIS, electrochemical impedance spectroscopy; IC, ion chromatography; ICP-OES, inductively coupled plasma optical emission spectrometry; LOD, limit of detection; LRR, linear response range; RMSE, root-mean-square error; SNR, signal-to-noise ratio.

4. Microneedle sensors for in planta sensing: representative case studies and implications for smart agriculture

Having outlined the design and detection principles of the MN sensors, we now turn to representative in planta implementations. This section summarizes experimental demonstrations that illustrate how the concepts described above translate to real plant systems. Reported studies are organized according to the main analyte classes introduced in Section 2, and each example is discussed in terms of architecture, transduction mechanism, analytical performance and implications for crop monitoring and decision support.

4.1. Bioelectrical signals and ionic fluxes

Bioelectrical signals and ionic fluxes were among the first targets for MN-based sensors for plants, with early demonstrations focusing on bulk electrical measurements before advancing towards ion-selective detection. Table 3 summarizes the analytical performance, validation level, deployment setting, and applicability of MN platforms for bioelectrical and ionic monitoring. Since 2017, Lee and co-workers have published a series of MN-based electrodes for bioelectrical signal recording [21,33,136,137]. Although these probes featured microscale tips on millimeter-scale probes and were not strictly MNs, they represented an early demonstration of direct electrical interfacing with living plants (Fig. 4a). Conductivity, resistance, impedance, and capacitance measurements were used to infer bulk ionic fluctuations and diurnal patterns

[124]. Rosati et al. introduced a new fabrication method based on inkjet-printed metallic MNs patterned onto flexible substrates (Fig. 4b) [127]. More recently, flexible MN arrays have been engineered to maintain stable contact with plant stems under bending conditions (Fig. 4c) [31]. The MN sensor detects electrophysiological responses associated with physical disturbances such as touching or cutting. Machine-learning (ML) algorithms were used to decode complex electrical signals for early stress detection, illustrating the potential of MN-based electrophysiological sensing for monitoring plant stress responses.

Altogether, the MN platforms for bulk electrical and electrophysiological monitoring provide time-resolved, but chemically nonspecific, indicators of plant status. These studies support the feasibility of resolving plant electrical responses under the respective experimental conditions [31,124]. However, they are not directly comparable and describe signal quality rather than ion-selective or concentration-based analytical accuracy. On the other hand, the reported in planta monitoring windows ranged from hours [127] to 13 d in a growth chamber [124], demonstrating the potential of these platforms for prolonged signal acquisition. Nevertheless, this long-term operation should be interpreted cautiously. First, the absence of selective receptors or functional coatings may make the system less susceptible to thermal instability, biofouling, or interface drift. Also, no validation with an alternative method has been reported. Despite these limitations, the stress-response classification achieved using machine-learning analysis [31] highlights the potential of these approaches for early stress

Table 4
Microneedle sensors for ROS, phytohormones, metabolites, and small molecules detection.

Analytes	Architecture	Transduction	Analytical features	Validation level	Deployment setting	Applicability details	ref
H ₂ O ₂ , glucose, pH	Hollow MN array	Amperometry	H ₂ O ₂ : LRR: 10–100 μ M; Sensitivity: $-3.2 \text{ nA } \mu\text{M}^{-1}$ Glucose: LRR: 50–1500 μ M; Sensitivity: $-0.6 \text{ nA } \mu\text{M}^{-1}$ pH: LRR: 5–8; Sensitivity: -71.0 mV pH^{-1} Sap extraction: $2.20 \pm 0.30 \text{ mg in 1 min}$; LRR: 0–500 $\mu\text{g mL}^{-1}$	In planta without validation	Laboratory	Discrete multianalyte measurements after sap extraction; no continuous monitoring	[27]
H ₂ O ₂	Solid MN	Extraction with colorimetric detection		In planta without validation	Laboratory	Discrete measurements	[24]
H ₂ O ₂	Implantable microelectrode	Amperometry	LRR: 5–200 μ M; Sensitivity: $0.0239 \text{ } \mu\text{A } \mu\text{M}^{-1}$; LOD: 0.35 μ M	In planta with partial validation against KI-based UV spectrophotometry	Environmentally controlled plant factory	Self-powered H ₂ O ₂ monitoring; 50 h continuous in vivo operation	[129]
H ₂ O ₂	Solid MN	Amperometry	LRR: 0.1–4500 μ M; Sensitivity: $14.7 \text{ } \mu\text{A } \mu\text{M}^{-1}$; LOD: 0.06 μ M	In planta with validation against Amplex Red fluorescence assay	Laboratory	Discrete measurements	[110]
Glucose	Solid MN array	Amperometry	LRR: 0–2 mM; Sensitivity: $17.27 \text{ } \mu\text{A mM}^{-1} \text{ cm}^{-2}$; LOD: 113 μ M	In planta without validation	Laboratory	Discrete measurements	[130]
Glucose	Hollow MN	Amperometry	LRR: 100 μ M–100 mM; Sensitivity: $17 \text{ nA } \mu\text{M}^{-1} \text{ cm}^{-2}$; LOD: 33.3 μ M	In planta without validation	Laboratory	Continuous glucose monitoring up to 12 h.	[115]
Glucose, H ₂ O ₂	Hollow MN with integrated microfluidic	CV	Glucose: LRR: 0–0.44 mM; Sensitivity: $62.34 \text{ } \mu\text{A mM}^{-1}$; LOD: 102.5 μ M. H ₂ O ₂ : LRR: 0–80 μ M; Sensitivity: $3.65 \text{ } \mu\text{A decade}^{-1}$; LOD: 3.22 μ M.	In planta without validation. Ex-vivo validation	Greenhouse	Discrete measurements	[116]
Glucose	Solid MN	Amperometry	LRR: 0–30 mM; Response time: 0.4 s	In planta without validation	Laboratory	Sensor retained in the leaf for 4 d; repeated 60-s measurements distinguished light/dark responses	[131]
IAA	Solid wire	DPV	LRR: 100 pg mL^{-1} to 100 $\mu\text{g mL}^{-1}$; LOD: 43 pg mL^{-1} ; LOQ: 143 pg mL^{-1} ; Sensitivity: 0.275 (log I vs. log C); RSD: 7% (n = 12)	In planta with validation against UPLC-MS	Laboratory	Monitoring under salt stress	[132]
IAA, SA	Solid MN	Multipulsed amperometry	IAA: LRR: 5–150 μ M; LOD: 1.41 μ M; Lifetime: ~ 543 cycles in vivo (25–30 h) SA: LRR: 5–150 μ M; LOD: 1.15 μ M; Lifetime: ~ 543 cycles in vivo (25–30 h)	In planta with validation against UPLC-MS	Laboratory	Quasi-continuous IAA/SA measurements every 3 min for 25–30 h; periodic electrochemical cleaning required	[25]
Sucrose	Hollow hypodermic needle	Amperometry	LRR up to 60 mM; Sensitivity: $6.22 \text{ } \mu\text{A mM}^{-1} \text{ cm}^{-2}$; LOD: 100 μ M; Response time: 90 s–2 min; Stability: 86% initial signal for 72 h	In planta without validation	Laboratory	Day–night sucrose transport monitoring; 86% signal retention after 72 h.	[133]
SA	Solid conical MN-IDEs	Amperometry	LRR: up to 150 μ M; Sensitivity: $0.0312 \text{ } \mu\text{A } \mu\text{M}^{-1} \text{ mm}^{-2}$ (0–20 μ M), $0.004 \text{ } \mu\text{A } \mu\text{M}^{-1} \text{ mm}^{-2}$ (50–150 μ M), LOD: 2.74 μ M;	In planta without validation	Laboratory	Relative SA monitoring during fungal infection. Discrete measurements	[111]
ABA	Solid MN array	Amperometry	LRR: 0.012–495.2 μ M (pH 4–7); Sensitivity (pH 6.5): $1.628 \text{ } \mu\text{A } \mu\text{M}^{-1}$ (0.012–0.095 μ M), $0.263 \text{ } \mu\text{A } \mu\text{M}^{-1}$ (0.095–3.76 μ M), $0.071 \text{ } \mu\text{A } \mu\text{M}^{-1}$ (3.76–495.2 μ M); LOD: 0.002–0.005 μ M	In planta without validation	Laboratory	Discrete measurements	[32]
ABA	Solid microelectrode	Amperometry	LRR: 1–1000 ng mL^{-1} ; Specificity: 71%; Sensitivity: 78%; Accuracy: 77%; Analysis time: <10 min	In planta with validation UHPLC–MS/MS	Laboratory	Discrete measurements, 9 min assay.	[114]

Abbreviations: ABA, abscisic acid; CV, cyclic voltammetry; DPV, differential pulse voltammetry; IAA, indole-3-acetic acid; IDE, interdigitated electrode; KI, potassium iodide; LOD, limit of detection; LOQ, limit of quantification; LRR, linear response range; SA, salicylic acid; UHPLC–MS/MS, ultra-high-performance liquid chromatography–tandem mass spectrometry; UPLC–MS, ultra-performance liquid chromatography–mass spectrometry; UV, ultraviolet.

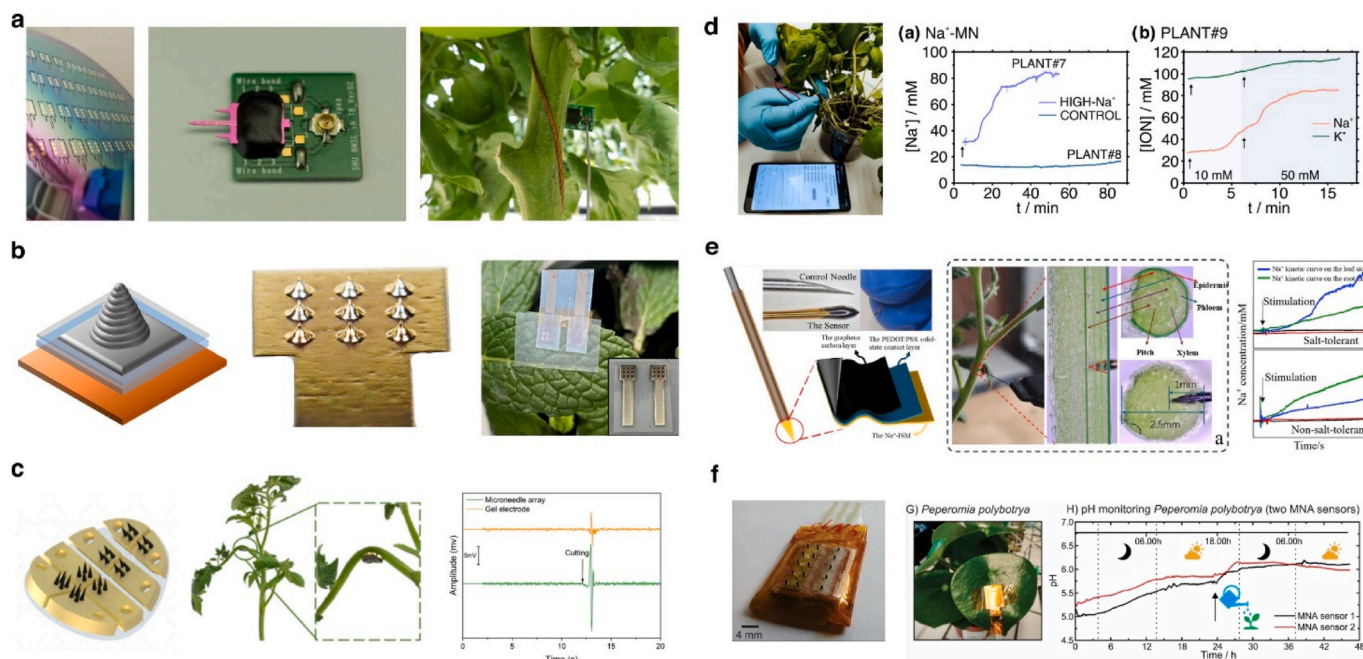


Fig. 4. (a) Electrical conductivity measurement for key plant physiological information via needle-shape sensors [33], reproduced from Ref. [33]. Copyright 2017 Institute of Physics Publishing. (b) All inkjet-printed conductive microneedles based on silver nanoparticles [127], reproduced from Ref. [127]. Available under CC BY4.0. (c) An implantable microneedle array using micromachining technology for monitoring and decoding plant electrical signals [31], reproduced from Ref. [31]. Copyright 2025 Elsevier. (d) Microneedle sensors for K⁺/Na⁺ monitoring to study ion dynamics in plants [28], reproduced from Ref. [28]. Available under CCBY4.0. (e) Microneedle sensors for Na⁺ ion monitoring to select salt-tolerant cultivars via rapid salt-level assessment [109], reproduced from Ref. [109]. Copyright 2025 Elsevier. (f) 3D-printed microneedle arrays for pH monitoring [125], reproduced from Ref. [125]. Copyright 2024 Elsevier.

screening and longitudinal trend recognition rather than analyte-resolved quantification, as a potential application for smart farming.

To address this lack of ion selectivity, later studies integrated carbon-based solid-contact transducers and ion-selective membranes onto stainless-steel MNs [28,109]. Commercial stainless steel MNs offer reliable conductivity and mechanical stability, serving as robust substrates for in planta sensor fabrication (Fig. 4d and e). The single-ion Na⁺ sensor reported by Fan et al. covered a concentration range from 10 μ M to 10 mM, with a near-Nernstian slope of 56.55 ± 0.25 mV dec⁻¹, and a response time below 10 s [109]. In addition, the multiplexed K⁺/Na⁺ platform reported by Wang et al. showed comparable slopes of approximately 55–57 mV dec⁻¹ and faster responses below 5 s, while extending the upper concentration limit to 100 mM for both ions [28]. In both cases, both detection limits (in the μ M) are already well below the mM concentrations targeted in these in planta measurements. Importantly, both platforms retained suitable analytical performance in artificial sap containing high concentrations of coexisting ions and in real plant sap samples. This matrix tolerance is a critical consideration for practical applicability because analytical performance established in simple buffer solutions cannot be directly extrapolated to complex plant matrices. Both systems were validated by comparison with reference techniques, ICP-OES for the single-ion Na⁺ sensor and ion chromatography for the multiplexed K⁺/Na⁺ platform, with no significant differences observed between the potentiometric and reference measurements. Compared with bulk electrical sensors, however, the potentiometric platforms demonstrated shorter continuous in planta monitoring periods: Na⁺ dynamics were followed for 3 h with the single-ion sensor, whereas the multiplexed platform achieved continuous K⁺ monitoring for up to 24 h.

Simultaneously, research efforts have been directed toward exploring alternative fabrication strategies such as additive manufacturing. Parrilla et al. recently applied commercial 3D printing to fabricate solid and hollow MN bodies for direct pH measurements and

biofluid extraction, respectively (Fig. 4f) [27,125]. The solid platform exhibited a near-Nernstian slope of -59.9 ± 1.5 mV pH⁻¹ over pH 4–8, a response time of 50 s. This analytical range fully covers the xylem pH window summarized in Section 2 (pH 5.0–6.5), although it does not encompass the upper end of the reported phloem range, which may reach pH 8.5. Continuous operation was demonstrated for 2–4 d, depending on the plant evaluated. However, operation remained restricted to laboratory conditions. By contrast, the hollow platform enabled sap extraction and subsequent external analysis, providing discrete measurements rather than continuous in planta monitoring. These examples demonstrate that the same manufacturing route can support either direct-sensing or extraction-based workflows, but fabrication versatility should not be mistaken for analytical maturity. The limited resolution of affordable stereolithography or digital light processing techniques constrains geometrical design, yielding wider insertion angles and larger hole diameters (>300 μ m) that increase tissue trauma. Additionally, the non-conductive nature of printable polymers requires complex post-fabrication metallization steps. Poor adhesion and mechanical stability of these functional layers on polymeric substrates can facilitate signal drift and membrane damage during insertion, ultimately limiting long-term measurement reliability [30,125].

More recent studies have explored alternative materials and interfaces to address the rigidity, potential drift, and limited analyte scope of earlier ion-selective MNs. Li et al. introduced a solid hydrogel MN coated with a conventional valinomycin-based PVC ISM, aiming to provide greater flexibility and a mechanically compliant interface with plant tissue [126]. The sensor tracked salt-induced K⁺ loss in rice and showed close agreement with IC measurements from parallel samples. However, in planta monitoring was limited to 60 min, and the low selectivity against Na⁺ requires further evaluation of the sensor under high-Na⁺ conditions before field deployment. Later, Wang et al. extended the analyte scope to the divalent cation Mg²⁺ using a stainless-steel all-solid-state MN-ISE with a compact graphene-composite solid contact that suppressed water-layer

formation, reduced potential drift, and enabled more than 40 h of xylem monitoring [123]. Nevertheless, accuracy could not be stated; undiluted pressed stem sap showed a pronounced positive matrix bias, whereas ICP-OES comparisons supported only treatment-dependent trends rather than absolute xylem concentrations.

Collectively, these potentiometric MN platforms illustrate the potential of monitoring rapid changes in ion concentrations associated with salt stress and nutrient status, providing chemically specific information that could support early stress assessment and more responsive irrigation or fertilization management. The remaining analytical and technological challenges for field deployment are discussed in greater detail in Sections 5.1–5.3 and 6.1–6.2.

4.2. Phytohormones, metabolites and reactive species

Beyond electrophysiological signals and ions, MN sensing platforms have been extended to track phytohormones, primary metabolites, and reactive species. While providing complementary insights into plant metabolic dynamics and systemic stress responses, these distinct analyte classes present markedly different analytical challenges, ranging from transient nanomolar fluctuations to high matrix interference. Accordingly, the following discussion critically examines ROS markers, primary sugars, and phytohormones individually, evaluating their dynamic ranges, matrix compatibility, operational stability, and validation strategies. Table 4 provides a comprehensive synthesis of reported MN architectures tailored for these targets.

Overall, H_2O_2 is currently the most extensively explored ROS target in MN-based plant sensing, although the number of reported platforms remains limited. Two main MN-based configurations have been investigated: direct electrochemical measurement at the plant-sensor

interface and MN-assisted sap extraction followed by *ex situ* analysis. Within the first group, Singh et al. (Fig. 5a) [110] reported an amperometric MN sensor capable of detecting pathogen-induced oxidative stress in real time. A solid MN was externally modified with horseradish peroxidase (HRP) enzyme, enabling H_2O_2 detection in the μM range directly inside plant tissue (LOD 0.06 μM). This analytical range comfortably covered the H_2O_2 concentrations measured in mock-treated and pathogen-inoculated tobacco and soybean leaves, which ranged from approximately 0.56 to 6.9 μM . Moreover, comparison with the Amplex Red fluorescence assay showed close agreement, supporting both the fit-for-purpose sensitivity and the accuracy of the *in planta* measurements. Importantly, however, each determination was discrete and required approximately 1 min, which may miss short-lived ROS transients occurring over seconds or less. In addition, continuous operation of the same MN sensor was not investigated.

Extraction-based platforms showed a complementary analytical profile. Parrilla et al. coupled hollow-MN-assisted sap collection with a Prussian-blue electrochemical sensor operating over 10–100 μM [27]. Notably, the lower limit of this range was above the approximately 0.56–6.9 μM H_2O_2 concentrations quantified by Singh et al. suggesting that the extraction-based platform may be better suited to detecting larger oxidative increases than lower- μM H_2O_2 levels. Comparison with plant fluid collected by conventional centrifugation supported the feasibility of the MN-assisted sampling procedure. However, because the samples obtained through both collection methods were analyzed using the same MN platform, this experiment compared sampling approaches rather than validating the measured H_2O_2 concentrations against an independent reference assay.

Wu et al. adopted a fundamentally different strategy using hydrogel MNs for sap extraction (2.20 ± 0.30 mg in 1 min) followed by *ex situ*

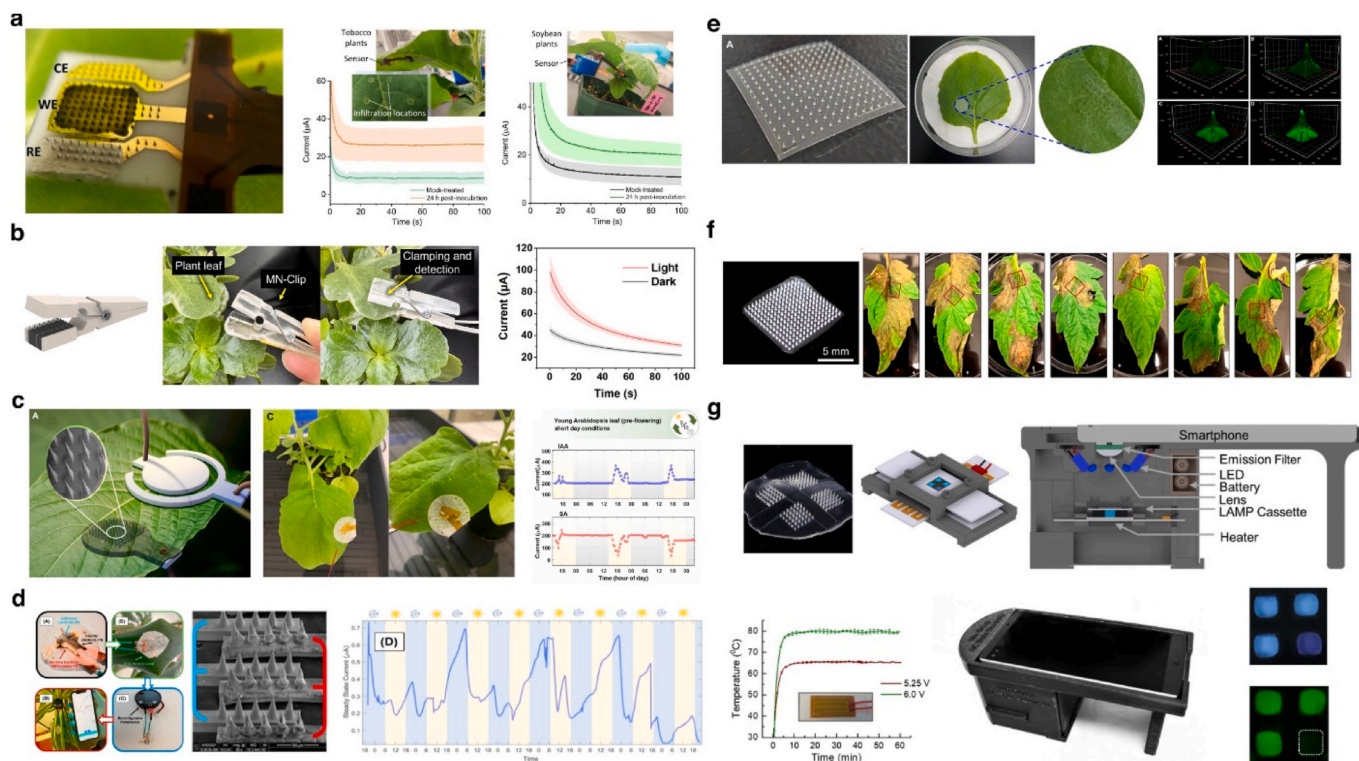


Fig. 5. (a) Microneedle array based on HRP/Cs-rGO hydrogels for H_2O_2 testing, reproduced from Ref. [110]. Copyright under CCBY-NC-ND 4.0. (b) Non-enzymatic $K-Co_3O_4$ microneedle clip for glucose detection [130], reproduced from Ref. [130]. Copyright 2025 Elsevier. (c) Leaf-adhered microneedle sensors for foliar IAA and SA detection [25], reproduced from Ref. [25]. Copyright 2025 The American Association for the Advancement of Science. (d) Conical MNs combined with interdigitated electrodes (IDE) combs for SA detection [111], reproduced from Ref. [111]. Copyright 2022 Elsevier. (e) Absorbent MNs with a catalytic hairpin assembly (CHA) detection system for miRNA detection [138], reproduced from Ref. [138]. Copyright 2024 Elsevier. (f) Disposable polymeric MN patch for rapid DNA extraction and analysis [26], reproduced from Ref. [26]. Copyright 2019 American Chemical Society. (g) Integrated MN-smartphone nucleic acid amplification platform with LAMP reaction and detection [22], reproduced from Ref. [22]. Copyright 2021 Elsevier.

colorimetric detection (LRR: 0–500 $\mu\text{g mL}^{-1}$). While sacrificing real-time monitoring, this extraction-based method avoids enzyme stability issues and biofouling associated with prolonged in planta measurements [24]. This contrast reflects two distinct paradigms in MN-based plant sensing: continuous in situ monitoring versus sample extraction with subsequent analysis. Finally, although not strictly MN-based, the implantable microsensor developed by Zhang et al. provides a useful benchmark for system-level deployment integrating H_2O_2 detection with photovoltaic power generation, data acquisition, and wireless transmission, enabling autonomous continuous monitoring of responses to osmotic, mechanical-injury, and UV stress operating for up to 50 h [129]. Although the sensor achieved an LOD of 0.35 μM in PBS, only H_2O_2 additions of approximately 100 μM could be resolved in untreated tomato sap, which further demonstrates that buffer-derived figures of merit cannot be directly extrapolated to authentic plant matrices without assessing analyte stability and performing matrix-specific calibration. Quantification was compared with a conventional potassium-iodide (KI) spectrophotometric assay, which was restricted to the osmotic-stress experiment. Thus, the study represents a strong engineering deployment, but only limited analytical validation in authentic plant matrices. Taken together, these studies indicate that H_2O_2 sensing could provide an early warning of biotic and abiotic stress and inform timely crop-management decisions. However, most reported MN platforms remain limited to discrete measurements, and few combine adequate sensitivity in authentic plant matrices with the temporal resolution required to resolve short-lived ROS transients, limiting their integration into real-time crop-monitoring workflows.

Among MN sensors developed for primary metabolite monitoring, particularly glucose, Chen et al. demonstrated the conventional enzymatic approach using hollow MNs containing glucose-oxidase-AuNP-decorated platinum microwires [115]. Glucose oxidase catalyzes glucose oxidation, generating H_2O_2 as a byproduct that is subsequently detected amperometrically. The sensor exhibited an LRR of 100 μM –100 mM and an LOD of 33.3 μM . This broad range extends well into the high-mM regime and is therefore more relevant for in planta measurements than further reductions in LOD, because glucose is already expected at comparatively high concentrations. The encapsulation of the GOx within hollow MN structures combined with Nafion/polyurethane protective coatings enabled continuous operation for up to 12 h. Although the recorded profiles were consistent with literature-expected diurnal glucose trends, they were not compared with an independent reference method. A complementary extraction-based strategy was previously demonstrated by Parrilla et al. The same 3D-printed hollow-MN platform discussed above for H_2O_2 also incorporated a GOx-based glucose channel operating over 50–1500 μM . However, sap collection and downstream analysis remained discrete rather than continuous [27]. More recently, Erukainure et al. proposed a more integrated system in which syringe-assisted vacuum drew sap through a sealed microfluidic pathway from the hollow MN array to tissue-isolated Au transducers functionalized with GOx or HRP for dual glucose/ H_2O_2 detection [116]. The glucose channel was linear over 0–0.44 mM (LOD: 102.5 μM), a narrower range than that of the Parrilla platform, which may limit direct quantification when sap glucose exceeds the upper calibration limit. For H_2O_2 , the system covered 0–80 μM with an LOD of 3.22 μM . Quantitative accuracy was evaluated ex vivo in extracted maize sap. In planta, however, syringe-assisted vacuum sampling and discrete measurements at selected time points were used to distinguish responses among graded watering treatments; the corresponding concentrations were not independently validated, and continuous monitoring was not demonstrated. Thus, the main advance lies in system integration and matrix-based ex vivo validation rather than continuous quantitative in planta sensing. On the other hand, Yun et al. (Fig. 5b) [130] developed a non-enzymatic glucose MN sensor based on potassium-doped Co_3O_4 ($\text{K-Co}_3\text{O}_4$) nanocatalysts integrated into a compact leaf-clipping device (LRR: 0–2 mM, LOD: 113 μM). Although the biocompatibility of the $\text{K-Co}_3\text{O}_4$ nanocatalysts was evaluated, key

concerns regarding their implementation in plant-based sensing remain unaddressed, particularly the potential for entry into the food chain. Moreover, non-enzymatic metal oxide sensors are inherently susceptible to biofouling, which can gradually degrade sensitivity and selectivity over time. The short measurement windows reported (<2 min) are insufficient to evaluate long-term operational stability, leaving open the question of whether this non-enzymatic approach offers a real advantage over conventional glucose oxidase-based sensors under in vivo conditions. More recently, Kim et al. incorporated a Co_3O_4 /MWCNT/chitosan composite into a 3D-printed MN platform, extending the in vitro glucose range to 0–30 mM and resolving light–dark signal differences over four days [131]. However, the in planta data were obtained from 60-s amperometric measurements rather than uninterrupted multi-day monitoring and were not validated against an independent analytical method. Finally, sucrose sensing has also been demonstrated using a hollow-needle platform based on a three-enzyme cascade comprising invertase, mutarotase, and glucose oxidase [133]. The sensor exhibited an LRR up to 60 mM, an LOD of 100 μM , and response times of 90 s–2 min, providing sufficient analytical coverage for the sucrose concentrations reported in the stem and fruit tissues investigated. The device retained 86% of its initial response after 72 h, although the in planta sucrose concentrations were not validated against an independent analytical reference method. Overall, glucose and sucrose monitoring could reveal diurnal carbon dynamics and changes in plant metabolic status. However, their use in crop management will require improved long-term operational stability and independent validation of the recorded temporal profiles.

Finally, phytohormones represent the most analytically demanding targets summarized in Table 4 due to their low concentrations, commonly within the nM– μM range, and large number of potential interferents. Reported MN platforms include direct electrochemical approaches, and receptor-mediated strategies based on antibodies or molecularly imprinted polymers. Regarding direct detection, Bukhamzin et al. introduced magnetized MNs coated with Fe_3O_4 -intercalated multi-walled carbon nanotubes to enhance electron transfer and increase the electroactive surface area of the sensing interface (Fig. 5c) [25]. The platform enabled simultaneous IAA and SA quantification with LODs of 1.41 and 1.15 μM , respectively. These values are suitable for detecting relatively large hormonal increases but may not fully cover basal nM or sub- μM concentrations. Quasi-continuous monitoring was demonstrated for approximately 25–30 h, with measurements acquired every 3 min, and the resulting concentrations showed moderate correlations with UHPLC–MS/MS measurements ($R^2 \geq 0.7$). Because analyte discrimination relies on separated oxidation potentials, the sensor is more susceptible to interference and progressive electrode passivation, requiring periodic electrochemical cleaning. In this regard, the same group explored the integration of magnetic molecularly imprinted polymers (MIPs) into MNs for selective SA recognition (Fig. 5d) [111]. The MIP layer improved discrimination against other phytohormones and reduced electrode fouling, although the higher LOD of 2.74 μM illustrates a trade-off between selectivity and sensitivity. Because selectivity was evaluated against a limited set of interferents and the PBS calibration could not be directly transferred to leaves, the platform was better suited to monitoring relative SA changes than to independently validated absolute quantification. By contrast, the Au@S-nO₂-vertical-graphene ABA sensor exploited the synergistic electrocatalytic and conductive properties of the nanocomposite to achieve one of the lowest LODs reported for MN-based phytohormone sensing, ranging from 2 to 5 nM (Table 4) [32]. However, this low-nM performance was established in PBS and was strongly pH-dependent. Recoveries of 93.3–108.9% were obtained in extracted cucumber juice, but the in planta measurements were brief (~500 s) and were not validated against an independent reference method; therefore, their quantitative accuracy remains unconfirmed.

Within another recognition-mediated approach, a wearable electrochemical lateral-flow (eLF) platform combined MN-assisted sap

extraction with a competitive ABA immunoassay [114]. The use of antibody-based molecular recognition enabled one of the lowest reported LODs (2 nM) together with UHPLC–MS/MS comparison, while achieving 78% diagnostic sensitivity, 71% specificity, and 77% classification accuracy during a three-week drought-stress study. However, these gains in analytical performance required integration into a lateral-flow immunoassay, increasing assay complexity and limiting the platform to discrete rather than continuous measurements. Current phytohormone platforms reveal a clear trade-off between sensitivity, molecular specificity, temporal resolution, and assay complexity. Direct electrochemical sensors favor repeated in planta measurements, whereas affinity-based approaches provide stronger selectivity and validation but remain largely limited to discrete analysis. The choice of strategy should therefore reflect whether the intended application prioritizes temporal tracking or highly selective quantification.

4.3. Pathogen and pesticide biomarkers

Pathogen-associated biomarkers and pesticide residues represent emerging targets for MN-assisted plant analysis. While ROS and phytohormones can provide early but nonspecific indications of plant stress, pathogen identification requires molecularly specific targets, particularly DNA or RNA [110,139]. Because nucleic-acid analysis remains analytically complex, the few MN platforms reported to date have focused primarily on minimally invasive sampling coupled with downstream optical detection, often following amplification, rather than on continuous in planta sensing. Table 5 summarizes the analytical performance, validation level, deployment setting, and applicability of pathogen- and pesticide-related MN platforms.

Chen et al., who reported a method for detecting plant microRNAs (specifically miR156 in tobacco, *Nicotiana benthamiana*), used MN-assisted sap extraction followed by on-site fluorescence-based quantification (Fig. 5e) [138]. A more integrated approach was later reported by Paul et al., who developed a MN patch capable of extracting nucleic acids (DNA and RNA) from plant leaves within 1 min, with the extracted genetic material remaining stable on the MN surface for up to three days (Fig. 5f) [26]. The same group subsequently introduced an integrated MN–smartphone platform combining loop-mediated isothermal amplification (LAMP) with optical readout for genomic DNA detection from tomato, potato, and chili leaves, successfully identifying *Phytophthora infestans* in infected tissues (Fig. 5g) [22]. Although optical readout was used, these studies highlight the potential of MN-assisted biofluid

sampling for molecular pathogen detection, which could be readily coupled with electrochemical readouts, extending their applicability. Pesticide-residue sensing has also been explored using a SERS-active hydrogel MN patch, in which the needles collected residues from within agricultural products while the patch base sampled surface contamination. The captured thiram and thiabendazole were subsequently analyzed on the patch by Raman spectroscopy, with LODs of 10^{-7} and 10^{-8} M, respectively [23]. Thus, the MN primarily served as a minimally invasive sampling interface for discrete *ex situ* analysis rather than as a continuously implanted sensor. Pathogen- and pesticide-related MN platforms remain at an earlier stage of integration into field-deployable systems, as most use MNs primarily as minimally invasive sampling interfaces followed by laboratory or discrete on-site analysis. The current literature therefore mainly provides proof-of-concept evidence that analytically demanding molecular assays can be coupled to MN sampling, rather than demonstrating mature tools for routine crop-monitoring and decision-support workflows.

5. Technical and analytical challenges for in planta microneedle sensing

5.1. Analytical figures of merit

Reliable quantification remains one of the main analytical challenges for MN-based plant sensing. In most studies, figures of merit such as sensitivity, LOD, and LRR are determined under controlled conditions using standard buffers rather than plant biofluids. However, plant sap contains complex mixtures of ions, metabolites, proteins, and phenolic compounds that can introduce interferences and alter sensor response [14]. A major limitation to expanding the range of detectable analytes, and, consequently, the scope of potential applications, is the availability of recognition elements with sufficient selectivity, stability, and compatibility with plant biofluids. Accordingly, the availability and performance of ionophores, enzymes, antibodies, and other affinity receptors constrain both sensor design and practical deployment.

Another aspect, and frequently overlooked in the literature, is the lack of precision regarding the exact plant compartment being sampled (i.e., apoplastic fluid, xylem sap, or phloem exudate). Despite substantial differences in ionic composition, pH, and co-existing interfering species among these matrices, this ambiguity persists. Such a gap severely complicates the rational selection of analytical parameters, including the sensor's linear range and relevant interferents, as well as the design

Table 5
Microneedle sensors for pathogen- or pesticide-related markers detection.

Analytes	Architecture	Sensing transduction	Analytical features	Validation level	Deployment setting	Applicability details	ref
MicroRNA	Solid absorbent MNs	Fluorescence	LRR: 25–100 nM (in vitro); LOD: 500 nM (in planta); Sensitivity: 30.54 a.u./nM	Collected samples without validation	Laboratory	Discrete miR156 detection in spiked tobacco leaves; Central laboratory CLSM fluorescence readout required	[138]
Pesticides	Solid MN patch	Surface-Enhanced Raman Spectroscopy (SERS)	Thiram: LRR = 10^{-4} - 10^{-7} M; LOD 10^{-7} M; Enhancement Factor: 692.59 Thiabendazole: LRR 10^{-5} – 10^{-8} M, LOD 10^{-8} M; Enhancement Factor: 816.91	Agricultural samples without independent validation	Laboratory testing of agricultural samples	Discrete measurement; Central laboratory Raman/SERS instrumentation required	[23]
DNA	Solid MN	Fluorescence/Colorimetry	LOD: 1 pg; LRR: 1 pg to 10 ng; sensitivity: 97.5–100%; specificity: 100%	Collected samples validation against benchtop amplification	Laboratory testing of laboratory-collected samples	Multiplex <i>P. infestans</i> /TSWV diagnosis within 30 min; On-site analysis	[22]
DNA	Solid MN	Nucleic acid extraction + PCR/qPCR	Detection rate: 100% for samples ≥ 3 days post-inoculation and all field samples; qPCR sensitivity: down to 1.2 pg/ μ L <i>P. infestans</i> DNA	Collected samples with validation against conventional CTAB extraction	Laboratory testing of field-collected samples	<i>P. infestans</i> DNA extraction in 1 min; Central laboratory PCR/qPCR equipment required	[26]

Abbreviations: CLSM, confocal laser scanning microscopy; CTAB, cetyltrimethylammonium bromide; LOD, limit of detection; LRR, linear response range; PCR, polymerase chain reaction; qPCR, quantitative polymerase chain reaction; SERS, surface-enhanced Raman spectroscopy.

of appropriate calibration protocols. Indeed, many studies still rely on deionized water or simplified artificial matrices that poorly replicate the actual sensing environment, neglecting not only chemical composition but also critical physical properties like viscosity, which directly dictate mass transport. Notably, this limitation extends beyond MN-based approaches; conventional destructive sampling methods are equally susceptible to cross-contamination between vascular compartments during tissue extraction. The resulting mixed fluid compositions obscure the true biochemical profile of any single compartment, consequently compromising the validation of *in planta* measurements. Definitive interpretation of *in planta* datasets therefore demands not only well-characterized sensors but also an unambiguous understanding of the specific target matrix being accessed, a fundamental prerequisite that remains insufficiently addressed across the field.

A closely related bottleneck is signal degradation driven by surface biofouling at the sensor–plant interface, a ubiquitous phenomenon that threatens all electrochemical modalities, including potentiometric, amperometric, and impedimetric sensors. Macromolecules present in plant sap, such as polysaccharides, proteins, and phenolic compounds, can adsorb non-specifically onto electrode surfaces, progressively deteriorating the sensor's response. While protective antifouling strategies like Nafion [140], polymer coatings [141–143] or hydrophilic surface treatments [144] have been explored to mitigate these matrix effects, they often introduce clear trade-offs, such as increased fabrication complexity or attenuated electrochemical responsiveness.

5.2. Field deployment challenges and environmental robustness

To date, nearly all *in planta* MN studies have been conducted under controlled laboratory environments; however, translation to field deployment introduces a distinct suite of challenges that transcend basic analytical performance. Achieving stable and reproducible measurements over extended periods, ranging from several days to weeks, remains a critical bottleneck, as reliable multi-day continuous operation is rarely demonstrated in the literature. Ambient environmental fluctuations drive this limitation. For instance, temperature variations directly modulate potentiometric responses as dictated by the Nernst equation [145], while simultaneously compromising the catalytic kinetics of enzymatic amperometric architectures [146].

Similarly, dynamic pH fluctuations within the plant sap can alter enzyme conformation and activity, introducing confounding measurement errors. Beyond these chemical variables, physical factors such as relative humidity, solar irradiance, and mechanical stress induced by wind or localized tissue expansion can jeopardize both the structural integrity of the MN arrays and the stability of the biotic–abiotic interface. Consequently, integrating co-localized auxiliary sensors, such as temperature probes or pH-sensitive MNs, to actively monitor and compensate for these environmental variables represents an indispensable design strategy for securing robust, long-term *in planta* operation [105].

Beyond compensation for environmental fluctuations, reliable long-term field operation requires demonstrating that sensor calibration remains valid over time. Biofouling, degradation of functional layers, and changes at the plant–sensor interface may cause baseline drift, loss of sensitivity, or slower response even while the device continues to generate a signal. Field-ready systems will therefore require predefined recalibration and validation strategies, including acceptable drift limits, recalibration intervals, and periodic comparison with independent reference methods. *In situ* drift-monitoring and temperature-supervised calibration approaches developed for field-deployed potentiometric sensors provide a useful precedent [145], although their applicability to *in planta* MN systems remains to be demonstrated. Long-term studies should therefore assess analytical performance over time rather than report operational duration alone.

Measurement reproducibility under field conditions represents an additional challenge. Variations in measurement-site selection and MN

insertion depth, angle, and force can alter the tissue compartment accessed and, consequently, the analytical response. Field-ready systems will therefore require standardized insertion and measurement protocols, ideally supported by automated applicators, to reduce operator-dependent variability and enable reproducible measurements across plants.

Field applicability must also account for the biological representativeness of the measurement. Although an MN may provide an analytically accurate local signal, insertion-induced tissue perturbation can alter the sampled microenvironment, with effects depending on MN geometry, insertion conditions, and the plant species and organ. Since mechanical wounding can rapidly induce responses such as local and systemic H_2O_2 accumulation, these effects should be characterized and accounted for when interpreting early post-insertion signals [147,148].

Manufacturing scalability represents a further barrier. As discussed in Section 3.1, many MN platforms rely on multistep and partly manual fabrication procedures, including MN preparation, surface modification, and deposition of functional sensing layers. These processes can introduce device-to-device and batch-to-batch variability in mechanical and electrochemical performance. Scalable manufacturing will therefore require reproducible fabrication and functionalization routes, together with cost-effective quality-control procedures.

Ultimately, long-term validation under greenhouse and field conditions, together with compact, low-power electronics for signal acquisition and data transmission, will be required for practical deployment (Section 6.1).

5.3. Mechanical and biological interface

The interaction between MNs and plant tissues strongly influences both signal stability and plant health. From a sensing perspective, incomplete MN penetration can limit access to the target plant compartment, resulting in sampling from unintended tissue layers. Moreover, variations in insertion depth directly affect the electroactive area in contact with the matrix. Both factors ultimately compromise the accuracy and reproducibility of quantitative measurements. This challenge is further compounded by the marked mechanical heterogeneity of plant tissues, not only across species, but also among different organs and developmental stages within the same plant. In addition, long-term monitoring must contend with plant growth since tissue expansion and developmental changes can progressively alter the mechanical stability of the sensor–tissue interface over time. At the same time, MN insertion may induce local wound responses, including ion redistribution and ROS accumulation, which can modify the composition of the sampled microenvironment and bias the analytical readout. Although most studies report that short MNs (<1 mm) cause minimal visible damage, quantitative assessments of tissue perturbation remain scarce. Future studies incorporating physiological indicators (e.g., growth rate, ion leakage) and molecular responses, such as ROS accumulation or microscopic structural analysis, could provide valuable insights. Correlating these parameters with the sensor readout would help discriminate between local tissue damage and systemic responses, ultimately guiding the design and optimization of less invasive MN sensors.

6. Emerging directions for *in planta* microneedle technologies

6.1. Fully integrated and flexible microneedle interfaces

Wearable sensors in human health rely on flexible substrates that maintain intimate contact with the skin [149]. In plant systems, analogous platforms must conform to diverse organs such as leaves, stems, and roots while accommodating continuous growth and complex surface microstructures. These conditions impose constraints absent from human-oriented wearables, as plant surfaces exhibit markedly different physicochemical properties and dynamic growth behavior. Plant organs undergo rapid morphological changes (e.g., stem thickening or leaf

expansion over days rather than months), requiring substrates that stretch, bend, and adhere without impeding growth. Conventional rigid sensors lack such compliance and may stress seedlings or deform fragile tissues.

Similarly, commercial soil sensors are bulky and invasive, making them unsuitable for attachment to growing plants. As a result, supporting substrates must combine stretchability, bendability, transparency (to avoid shading), breathability and gentle adhesion, ensuring long-term device stability without obstructing photosynthesis [150]. Adhesion is further complicated by organ-specific epidermal features such as wax layers, stomatal patterns, trichomes, and superhydrophobic surfaces, which hinder conventional bonding strategies [151]. Conventional adhesives, ropes, or tapes should be avoided because they interfere with local growth. Biomimetic microstructures therefore offer a compelling route to conformal adhesion (Fig. 6) [152–158]. Natural designs such as hook-like trichomes, thorns, microhooks, or the ratchet-like anchoring of *Galium aparine* inspire mechanical interlocking MN patches that adhere through insertion and directional loading, without external adhesives or fixtures.

Beyond mechanical attachment, achieving fully autonomous sensing systems requires combining MN platforms with compact electronics for signal acquisition, processing, and wireless communication. In plant systems, however, such integration must remain lightweight to avoid

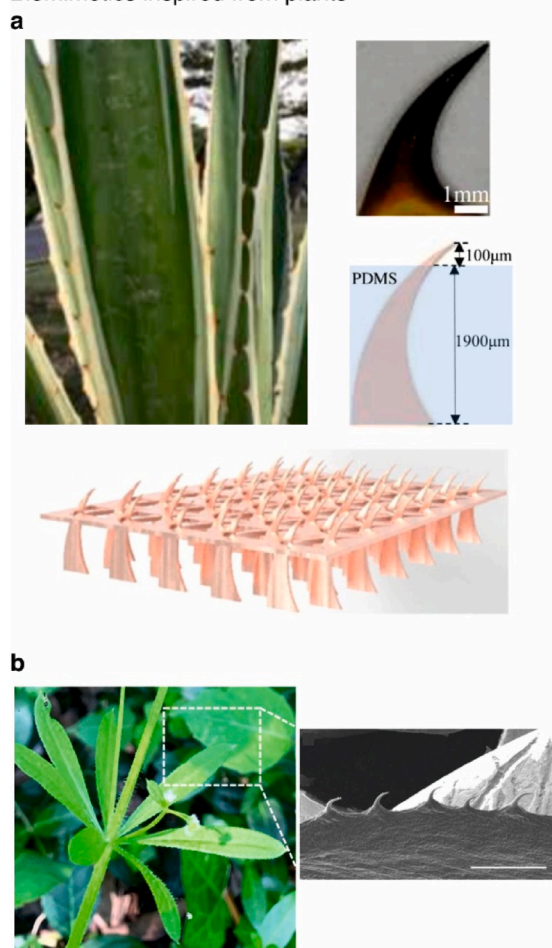
mechanical loading of stems or leaves during growth and environmental movement. Consequently, miniaturized and low-power electronic modules, such as Bluetooth Low Energy communication units, can be integrated into lightweight housings with flexible wiring to enable long-term operation while preserving plant integrity [159].

6.2. AI-driven analytics and multiplexed MN sensing

Single-analyte measurements in plants often lack diagnostic specificity, as similar biochemical signatures may arise from distinct stressors. For example, salicylic acid levels may increase during fungal infection, but also under drought stress [160,161]. Consequently, integrating information from multiple analytes and environmental variables is essential for reliable interpretation of plant physiological states. The large and heterogeneous datasets generated by plant sensing platforms, including electrochemical signals, environmental parameters, and plant physiological indicators, have increasingly motivated the use of AI and machine learning (ML) tools [162]. Recent wearable plant-monitoring systems illustrate how data-driven approaches can extract meaningful patterns from multimodal signals and predict stress responses earlier than conventional methods [163–165].

For MN-based sensing, this paradigm becomes particularly important as future devices aim to simultaneously monitor multiple chemical

Biomimetics inspired from plants



Biomimetics inspired from animals

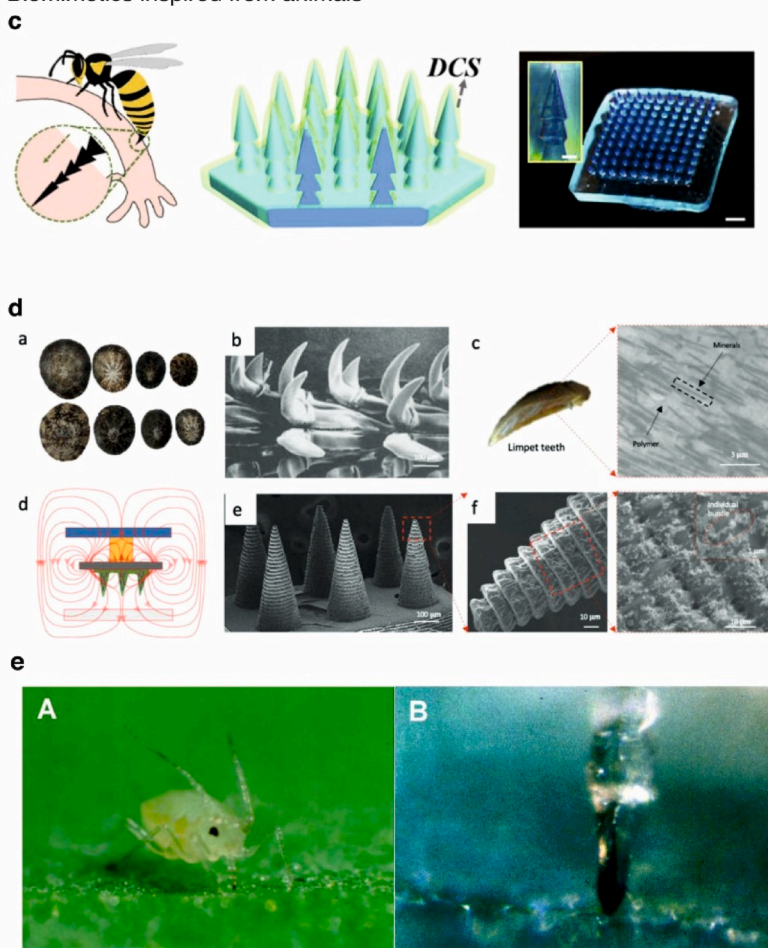


Fig. 6. (a) Picture of golden margined century plant leaf [156], reproduced from Ref. [156]. Copyright 2021 Elsevier. (b) Hooks on the leaf. Geometry and orientation of the structure of *G. aparine* plant [154], reproduced from Ref. [154]. Copyright 2024 John Wiley and Sons. (c) Schematic illustration of the sting of the wasp, and corresponding illustration of the multilayer microneedle patch with DCS coating [155], reproduced from Ref. [155]. Copyright 2021 Elsevier. (d) Limpet tooth-inspired 3D-printed MN array [158], reproduced from Ref. [158]. Copyright 2021 John Wiley and Sons. (e) Feeding aphid of the family Aphididae sucking on phloem sap [157], reproduced from Ref. [157]. Copyright under CC-BY-4.0. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

and physiological markers. Multiplexed MN arrays could combine detection of ions, hormones, metabolites, and environmental parameters, generating complex datasets that require advanced signal processing and pattern recognition to interpret plant health and stress responses. However, multiplexed MN sensing remains technically challenging. Integrating multiple sensing elements within compact MN platforms increases fabrication complexity and device dimensions, while high-density arrays introduce signal-processing challenges such as channel crosstalk and parasitic capacitances [166]. These issues can distort signals, particularly under wide dynamic ranges or high sampling frequencies. Future progress will therefore depend on co-designing MN arrays with advanced microfabrication strategies and optimized signal-processing architectures capable of supporting multi-parameter sensing within compact devices.

6.3. Living sensors and plant–material biohybrids

Plants possess intrinsic sensing capabilities, responding to environmental stimuli such as light, temperature, gravity, and mechanical perturbations through specialized receptors and complex signal-transduction networks [167]. These mechanisms regulate tropic responses and stress adaptation, highlighting that plants function as active information-processing systems. Plant tissues also exhibit remarkable tolerance to physicochemical modification, enabling the development of plant–material biohybrids. Recent studies show that plants can interface with organic electronic materials such as PEDOT:PSS and carbon-based nanomaterials (e.g., carbon nanotubes or graphene) without compromising viability [29,88]. Such compatibility arises from non-covalent interactions with cell-wall polysaccharides and from the ability of these materials to localize within vascular tissues. Taking advantage of this inherent compatibility, biohybrid platforms have been explored for integrating functional materials directly with living plants. For example, microfluidic printing onto leaves has enabled stable material integration for sensing and stimulation [168,169]. Although this concept remains at an early stage and has not yet been demonstrated with MN platforms, these studies illustrate how future MN systems could evolve toward biohybrid platforms capable of combining sensing with targeted intervention in plant physiological processes.

6.4. Closed-loop MN systems: integrating sensing and targeted chemical delivery

Closed-loop MN systems integrate real-time sensing with on-demand chemical delivery, enabling automated responses to plant stress. Such platforms combine sensing and actuation within a single device, allowing interventions to be guided by plant physiological signals. These concepts are particularly promising for high-value crops and controlled-environment agriculture, where intervention precision directly affects yield and quality [170]. A recent example was reported by Cao et al., who developed a silk-fibroin (SF) MN platform capable of high-volume agrochemical delivery while simultaneously monitoring contaminants such as Cd [30]. Although such closed-loop MN systems remain at an early stage, this work illustrates the potential of integrating sensing and chemical delivery within a single plant-interfacing device.

6.5. Commercial pathways, TRLs and on-the-field adoption

Transitioning MN sensors from proof-of-concept prototypes to commercial plant-monitoring technologies remains challenging. Key barriers include maintaining stable sensor performance in biological environments, mitigating biofouling, and establishing reliable calibration strategies that ensure quantitative accuracy under field conditions [14]. In addition, the integration of compact sensing electronics increases system complexity and cost, which may require modular architectures that decouple the sensing interface from processing units to enable scalable manufacturing. Regulatory and economic factors further

complicate commercialization. The absence of dedicated frameworks for *in planta* sensing devices raises uncertainties regarding environmental impact, biodegradability, and device disposal. At the same time, widespread adoption will depend on demonstrating clear agronomic and economic benefits through large-scale field validation. The Technology Readiness Level (TRL) framework provides a useful reference for assessing technological maturity. Based on the studies reviewed here, MN platforms for plant sensing currently correspond approximately to TRL 4–6, representing laboratory-validated prototypes tested in relevant environments but lacking large-scale field deployment and regulatory approval [171]. Although MN-based plant sensors are not yet widely commercialized, companies working in plant sensing and precision agriculture, such as Growera, InnerPlant, and Phyttech, illustrate the growing industrial interest in plant-integrated monitoring technologies.

7. Conclusion and remarks

Electrochemical MN sensors offer a promising approach for *in planta* chemical monitoring, transitioning plant diagnostics from retrospective laboratory assays to real-time, *in planta* measurements. Combined with scalable, low-cost manufacturing approaches, these platforms could complement existing precision-agriculture tools. However, translating these laboratory prototypes into field-deployable architectures requires the emerging field of plant bioelectronics to transcend its current boundaries. Further progress will require addressing the challenges at the plant–sensor interface by engineering elastomeric, mechanically compliant substrates that conform to dynamic tissue growth and achieve stable operation across plant tissues, species, and environmental conditions.

To unlock the potential of *in planta* MN sensing, future research must shift from simple proof-of-concept analyte detection toward holistic analytical robustness and multi-system integration. Reliable quantification in *in planta* requires improved antifouling and protective sensing layers, alongside integrated hardware and data-processing strategies for real-time temperature and background compensation. Also, single-analyte measurements often lack sufficient specificity to distinguish overlapping stress responses. Therefore, combining multimodal MN platforms with AI-driven multivariate data analysis could improve the interpretation of plant physiological states. Achieving these advances will require coordinated efforts across plant physiology, analytical chemistry, materials science, and engineering to define relevant targets, establish validation protocols, and develop stable, integrated MN systems for plant research, precision agriculture, and food security.

CRediT authorship contribution statement

Águeda Molinero-Fernández: Writing – review & editing, Writing – original draft, Resources, Conceptualization. **Qianyu Wang:** Writing – review & editing, Writing – original draft, Visualization, Resources, Conceptualization. **Maria Cuartero:** Writing – review & editing, Writing – original draft, Visualization, Resources, Conceptualization. **Gaston A. Crespo:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

- [1] M. Kah, N. Tufenkji, J.C. White, Nano-enabled strategies to enhance crop nutrition and protection, *Nat. Nanotechnol.* 14 (2019) 532–540.
- [2] H.C.J. Godfray, J.R. Beddington, L.R. Crute, L. Haddad, D. Lawrence, J.F. Muir, J. Pretty, S. Robinson, S.M. Thomas, C. Toulmin, Food security: the challenge of feeding 9 billion people, *Science* 327 (2010) 812–818.
- [3] S.C. Teixeira, N.O. Gomes, T.V. Oliveira, N.F.F. Soares, P.A. Raymundo-Pereira, Sustainable wearable sensors for plant monitoring and precision agriculture, *Anal. Chem.* 97 (2025) 14875–14884.
- [4] D. Presti, J. Tocco, C. Massaroni, S. Cimini, L. Gara, S. Singh, A. Raucchi, G. Manganiello, S.L. Woo, E. Schena, Current understanding, challenges and perspective on portable systems applied to plant monitoring and precision agriculture, *Biosens. Bioelectron.* 222 (2023) 115005.
- [5] N.V. Verma, M. Shukla, R. Kulkarni, K. Srivastava, B. Claudic, J. Savara, M. Joseph Mathew, R. Maurya, G. Bhattacharjee, V. Singh, Emerging extraction and diagnostic tools for detection of plant pathogens: recent trends, challenges, and future scope, *ACS Agricultural Science & Technology* 2 (2022) 858–881.
- [6] E. Esteves, G. Locatelli, N.A. Bou, R.S. Ferrarezi, Sap analysis: a powerful tool for monitoring plant nutrition, *Horticulturae* 7 (2021) 426.
- [7] L. Broussard, C. Abadie, J. Lalande, A.M. Limami, J. Lothier, G. Tcherkez, Phloem sap composition: what have we learnt from metabolomics? *Int. J. Mol. Sci.* 24 (2023) 6917.
- [8] P. Coatsworth, L. Gonzalez-Macia, A.S.P. Collins, T. Bozkurt, F. Güder, Continuous monitoring of chemical signals in plants under stress, *Nat. Rev. Chem.* 7 (2023) 7–25.
- [9] S. Getahun, H. Kefale, Y. Gelaye, Application of precision agriculture technologies for sustainable crop production and environmental sustainability: a systematic review, *Sci. World J.* 2024 (2024) 2126734.
- [10] N. Gangwani, AI-driven precision agriculture: optimizing crop yield and resource efficiency, *Int. J. Multidiscip. Res.* 6 (2024) 29913.
- [11] W. Xu, L. Chen, X. Hu, L. Zhang, D. Huang, J. Li, R. Xiong, C. Huang, M. Zhu, Botanic signal monitor: advanced wearable sensor for plant health analysis, *Adv. Funct. Mater.* 34 (2024) 2410544.
- [12] P.G. Steeneken, E. Kaiser, G.J. Verbiest, M.-C. Veldhuis, Sensors in agriculture: towards an internet of plants, *Nat. Rev. Methods Primers* 3 (2023) 60.
- [13] H. Yin, Y. Cao, B. Marelli, X. Zeng, A.J. Mason, C. Cao, Soil sensors and plant wearables for smart and precision agriculture, *Adv. Mater.* 33 (2021) 2007764.
- [14] Q. Wang, Á. Molinero-Fernández, J.R. Acosta Motos, G.A. Crespo, M. Cuartero, Microneedle sensors for ion monitoring in plants. One step closer to smart agriculture, *ACS Sens.* 10 (2025) 4771–4784, <https://doi.org/10.1021/acssens.5c01215>.
- [15] N. Seddaoui, F. Arduini, Recent advances in wearable and implantable electrochemical (bio) sensors for plant health monitoring, *TrAC, Trends Anal. Chem.* (2025) 118336.
- [16] B. Wang, H. Lu, S. Jiang, B. Gao, Recent advances of microneedles biosensors for plants, *Anal. Bioanal. Chem.* 416 (2024) 55–69.
- [17] S. Lee, S. Park, H. Sharma, M. Safdar, S. Park, W. Kim, D. Kim, J. Oh, J. Kim, Microneedle-Based precision engineering for agrochemical delivery and plant health monitoring in situ, *ACS Agricultural Science & Technology* 4 (2024) 768–780.
- [18] S. Kumari, N. Talreja, D. Chauhan, M. Ashfaq, Microneedle (MN)-based sensing technology: an innovative solution for agriculture, *Mater. Adv.* 5 (2024) 8745–8754.
- [19] Z. Faraji Rad, Microneedle technologies for food and crop health: recent advances and future perspectives, *Adv. Eng. Mater.* 25 (2023) 2201194.
- [20] E. Ece, I. Eş, F. İnci, Microneedle technology as a new standpoint in agriculture: treatment and sensing, *Mater. Today* 68 (2023) 275–297.
- [21] S. Baek, E. Jeon, K.S. Park, K.-H. Yeo, J. Lee, Monitoring of water transportation in plant stem with microneedle sap flow sensor, *J. Microelectromech. Syst.* 27 (2018) 440–447.
- [22] R. Paul, E. Ostermann, Y. Chen, A.C. Saville, Y. Yang, Z. Gu, A.E. Whitfield, J. B. Ristaino, Q. Wei, Integrated microneedle-smartphone nucleic acid amplification platform for in-field diagnosis of plant diseases, *Biosens. Bioelectron.* 187 (2021) 113312.
- [23] X. Yi, Z. Yuan, X. Yu, L. Zheng, C. Wang, Novel microneedle patch-based surface-enhanced Raman spectroscopy sensor for the detection of pesticide residues, *ACS Appl. Mater. Interfaces* 15 (2023) 4873–4882.
- [24] X. Wu, Y. Pan, X. Li, Y. Shao, B. Peng, C. Zhang, C. Zhang, S. Yao, J. Ping, Y. Ying, Rapid and In-Field Sensing of Hydrogen Peroxide in Plant by Hydrogel Microneedle Patch, *Small* 20 (38) (2024) 2402024.
- [25] A.H. Bukhamsin, S.S. Shetty, E. Fakeih, M.S. Martinez, C. Lerma, M. Mundummal, J.Y. Wang, J. Kosel, S. Al-Babli, I. Bililou, In vivo dynamics of indole- and phenol-derived plant hormones: Long-term, continuous, and minimally invasive phytohormone sensor, *Sci. Adv.* 11 (2025) eads8733.
- [26] R. Paul, A.C. Saville, J.C. Hansel, Y. Ye, C. Ball, A. Williams, X. Chang, G. Chen, Z. Gu, J.B. Ristaino, Extraction of plant DNA by microneedle patch for rapid detection of plant diseases, *ACS Nano* 13 (2019) 6540–6549.
- [27] M. Parrilla, A. Sena-Torralba, A. Steijlen, S. Morais, Á. Maquieira, K. Wael, A 3D-printed hollow microneedle-based electrochemical sensing device for in situ plant health monitoring, *Biosens. Bioelectron.* 251 (2024) 116131.
- [28] Q. Wang, Á. Molinero-Fernández, J.-R. Acosta-Motos, G.A. Crespo, M. Cuartero, Unveiling potassium and sodium ion dynamics in living plants with an In Planta potentiometric microneedle sensor, *ACS Sens.* 9 (2024) 5214–5223.
- [29] C. Diacci, T. Abedi, J.W. Lee, E.O. Gabrielson, M. Berggren, D.T. Simon, T. Niittylä, E. Stavrinidou, Diurnal in vivo xylem sap glucose and sucrose monitoring using implantable organic electrochemical transistor sensors, *iScience* 24 (2021) 101966.
- [30] Y. Cao, D. Kim, S.S. Koh, Z. Li, F. Rigoldi, J.E. Fortmueller, K. Goh, Y. Zhang, E. J. Lim, H. Sun, Nanofabrication of silk microneedles for high-throughput micronutrient delivery and continuous sap monitoring in plants, *Nat. Nanotechnol.* (2025) 1142–1151.
- [31] J. Zhou, P. Fan, S. Zhou, Y. Pan, J. Ping, Machine learning-assisted implantable plant electrophysiology microneedle sensor for plant stress monitoring, *Biosens. Bioelectron.* 271 (2025) 117062.
- [32] Z. Wang, L. Xue, M. Li, C. Li, P. Li, H. Li, Au@ SnO₂-vertical graphene-based microneedle sensor for in-situ determination of abscisic acid in plants, *Mater. Sci. Eng. C* 127 (2021) 112237.
- [33] E. Jeon, S. Choi, K.-H. Yeo, K.S. Park, M.L. Rathod, J. Lee, Development of electrical conductivity measurement technology for key plant physiological information using microneedle sensor, *J. Micromech. Microeng.* 27 (2017) 085009.
- [34] E. Domínguez, J. Cuartero, A. Heredia, An overview on plant cuticle biomechanics, *Plant Sci.* 181 (2011) 77–84.
- [35] T. Shepherd, D. Wynne Griffiths, The effects of stress on plant cuticular waxes, *New Phytol.* 171 (2006) 469–499.
- [36] L.J. Gibson, The hierarchical structure and mechanics of plant materials, *J. R. Soc. Interface* 9 (2012) 2749–2766.
- [37] Y. Wang, K.L. Marshall, Y. Baba, G.J. Gerling, E.A. Lumpkin, Hyperelastic material properties of mouse skin under compression, *PLoS One* 8 (2013) e67439.
- [38] B.B. Misra, The black-box of plant apoplast lipidomes, *Front. Plant Sci.* 7 (2016), <https://doi.org/10.3389/fpls.2016.00323>.
- [39] A. Farvardin, A.I. González-Hernández, E. Llorens, P. García-Agustín, L. Scalschi, B. Vicedo, The apoplast: a key player in plant survival, *Antioxidants* 9 (2020) 604, <https://doi.org/10.3390/antiox9070604>.
- [40] A. Kutrowska, M. Szela, Low-molecular weight organic acids and peptides involved in the long-distance transport of trace metals, *Acta Physiol. Plant.* 36 (2014) 1957–1968.
- [41] E.U. Alum, D.C. Obasi, J.N. Abba, U.C. Aniokete, P.N. Okoroh, O.P.-C. Ugwu, D. E. Uti, Endogenous Plant signals and human Health: molecular mechanisms, ecological functions, and therapeutic prospects, *Biochem. Biophys. Rep.* 43 (2025) 102114.
- [42] J.M. Ugalde, M. Schlößer, A. Dongois, A. Martinière, A.J. Meyer, The latest HyPe (r) in plant H₂O₂ biosensing, *Plant Physiol.* 187 (2021) 480–484.
- [43] T. Nietzel, M. Elsässer, C. Ruberti, J. Steinbeck, J.M. Ugalde, P. Fuchs, S. Wagner, L. Ostermann, A. Moseler, P. Lemke, The fluorescent protein sensor rGFP 2-Orp1 monitors in vivo H₂O₂ and thiol redox integration and elucidates intracellular H₂O₂ dynamics during elicitor-induced oxidative burst in Arabidopsis, *New Phytol.* 221 (2019) 1649–1664.
- [44] A. Vishwakarma, A. Wany, S. Pandey, M. Bulle, A. Kumari, R. Kishorekumar, A. U. Igamberdiev, L.A.J. Mur, K.J. Gupta, Current approaches to measure nitric oxide in plants, *J. Exp. Bot.* 70 (2019) 4333–4343.
- [45] D. Huo, D. Li, S. Xu, Y. Tang, X. Xie, D. Li, F. Song, Y. Zhang, A. Li, L. Sun, Disposable stainless-steel wire-based electrochemical microsensor for in vivo continuous monitoring of hydrogen peroxide in vein of tomato leaf, *Biosensors* 12 (2022) 35.
- [46] S. Akter, M.S. Khan, E.N. Smith, E. Flashman, Measuring ROS and redox markers in plant cells, *RSC Chem. Biol.* 2 (2021) 1384–1401.
- [47] O. Herud-Sikimić, A.C. Stiel, M. Kolb, S. Shanmugaratnam, K.W. Berendzen, C. Feldhaus, B. Höcker, G. Jürgens, A biosensor for the direct visualization of auxin, *Nature* 592 (2021) 768–772.
- [48] J. Rowe, M. Grangé-Guermente, M. Exposito-Rodriguez, R. Wimalasekera, M. O. Lenz, K.N. Shetty, S.R. Cutler, A.M. Jones, Next-generation ABACUS biosensors reveal cellular ABA dynamics driving root growth at low aerial humidity, *Nat. Plants* 9 (2023) 1103–1115.
- [49] R. Waadt, K. Hitomi, N. Nishimura, C. Hitomi, S.R. Adams, E.D. Getzoff, J. I. Schroeder, FRET-based reporters for the direct visualization of abscisic acid concentration changes and distribution in Arabidopsis, *eLife* 3 (2014) e01739.
- [50] R. Isoda, A. Yoshinari, Y. Ishikawa, M. Sadoine, R. Simon, W.B. Frommer, M. Nakamura, Sensors for the quantification, localization and analysis of the dynamics of plant hormones, *Plant J.* 105 (2021) 542–557.
- [51] M.C.-Y. Ang, J.M. Saju, T.K. Porter, S. Mohaideen, S. Sarangapani, D.T. Khong, S. Wang, J. Cui, S.I. Loh, G.P. Singh, Decoding early stress signaling waves in living plants using nanosensor multiplexing, *Nat. Commun.* 15 (2024) 2943.
- [52] S. Shabala, T.A. Cuin, L. Shabala, I. Newman, Quantifying kinetics of net ion fluxes from plant tissues by non-invasive microelectrode measuring MIFE technique, in: *Plant Salt Tolerance: Methods and Protocols*, Springer, 2012, pp. 119–134.
- [53] I.A. Newman, Ion transport in roots: measurement of fluxes using ion-selective microelectrodes to characterize transporter function, *Plant Cell Environ.* 24 (2001) 1–14.
- [54] M.T. Peña-Fleitas, M. Gallardo, F.M. Padilla, A. Rodríguez, R.B. Thompson, Use of a portable rapid analysis system to measure nitrate concentration of nutrient and soil solution, and plant sap in greenhouse vegetable production, *Agronomy* 11 (2021) 819.
- [55] K.S. Gjetting, C.K. Ytting, A. Schulz, A.T. Fuglsang, Live imaging of intra- and extracellular pH in plants using pHusion, a novel genetically encoded biosensor, *J. Exp. Bot.* 63 (2012) 3207–3218, <https://doi.org/10.1093/jxb/ers040>.
- [56] A. Martinière, G. Desbrosses, H. Sentenac, N. Paris, Development and properties of genetically encoded pH sensors in plants, *Front. Plant Sci.* 4 (2013) 523.

- [57] A. Martinière, R. Gibrat, H. Sentenac, X. Dumont, I. Gaillard, N. Paris, Uncovering pH at both sides of the root plasma membrane interface using noninvasive imaging, *Proc. Natl. Acad. Sci.* 115 (2018) 6488–6493.
- [58] C.-M. Geilfus, The pH of the apoplast: dynamic factor with functional impact under stress, *Mol. Plant* 10 (2017) 1371–1386.
- [59] H.H. Felle, pH: signal and messenger in plant cells, *Plant Biol.* 3 (2001) 577–591.
- [60] M.S. Wheatley, Y.-P. Duan, Y. Yang, Highly sensitive and rapid detection of citrus Huanglongbing pathogen ('Candidatus Liberibacter asiaticus') using Cas12a-based methods, *Phytopathology* 111 (2021) 2375–2382.
- [61] R. Lei, R. Kuang, X. Peng, Z. Jiao, Z. Zhao, H. Cong, Z. Fan, Y. Zhang, Portable rapid detection of maize chlorotic mottle virus using RT-RAA/CRISPR-Cas12a based lateral flow assay, *Front. Plant Sci.* 14 (2023) 1088544.
- [62] M.-C. Marqués, J. Sánchez-Vicente, R. Ruiz, R. Montagud-Martínez, R. Márquez-Costa, G. Gómez, A. Carbonell, J.-A. Darós, G. Rodrigo, Diagnostics of infections produced by the Plant Viruses TMV, TEV, and PVX with CRISPR-Cas12 and CRISPR-Cas13, *ACS Synth. Biol.* 11 (2022) 2384–2393, <https://doi.org/10.1021/acssynbio.2c00090>.
- [63] D.M. Alon, H. Hak, M. Bornstein, G. Pines, Z. Spiegelman, Differential detection of the tobamovirus Tomato Mosaic Virus (ToMV) and Tomato Brown Rugose Fruit Virus (ToBRFV) using CRISPR-Cas12a, *Plants* 10 (2021) 1256.
- [64] R. Lei, Y. Li, L. Li, J. Wang, Z. Cui, R. Ju, L. Jiang, X. Liao, P. Wu, X. Wang, A CRISPR/Cas12a-based portable platform for rapid detection of *Leptosphaeria maculans* in Brassica crops, *Front. Plant Sci.* 13 (2022) 976510.
- [65] R. Selvarajan, P.S. Kanichelvam, V. Balasubramanian, S.S. Subramanian, A rapid and sensitive lateral flow immunoassay (LFIA) test for the on-site detection of banana bract mosaic virus in banana plants, *J. Virol. Methods* 284 (2020) 113929.
- [66] N.A. Byzova, S. V Vinogradova, E. V Porotikova, U.D. Terekhova, A. V Zherdev, B. B. Dzantiev, Lateral flow immunoassay for rapid detection of grapevine leafroll-associated virus, *Biosensors* 8 (2018) 111.
- [67] N. Awaludin, J. Abdullah, F. Salam, K. Ramachandran, N.A. Yusof, H. Wasoh, Fluorescence-based immunoassay for the detection of *Xanthomonas oryzae* pv. *oryzae* in rice leaf, *Anal. Biochem.* 610 (2020) 113876.
- [68] M. Regiart, M. Rinaldi-Tosi, P.R. Aranda, F.A. Bertolino, J. Villarroel-Rocha, K. Sapag, G.A. Messina, J. Raba, M.A. Fernández-Baldo, Development of a nanostructured immunosensor for early and in situ detection of *Xanthomonas arboricola* in agricultural food production, *Talanta* 175 (2017) 535–541.
- [69] G. Zhang, C. Zhu, Y. Huang, J. Yan, A. Chen, A lateral flow strip based aptasensor for detection of ochratoxin A in corn samples, *Molecules* 23 (2018) 291.
- [70] Y. Liu, D. Liu, S. Cui, C. Li, Z. Yun, J. Zhang, F. Sun, Design of a signal-amplified aptamer-based lateral flow test strip for the rapid detection of ochratoxin A in red wine, *Foods* 11 (2022) 1598.
- [71] B. Chaudhuri, F. Hörmann, S. Lalonde, S.M. Brady, D.A. Orlando, P. Benfey, W. B. Frommer, Protonophore- and pH-insensitive glucose and sucrose accumulation detected by FRET nanosensors in Arabidopsis root tips, *Plant J.* 56 (2008) 948–962.
- [72] B. Chaudhuri, F. Hörmann, W.B. Frommer, Dynamic imaging of glucose flux impedance using FRET sensors in wild-type Arabidopsis plants, *J. Exp. Bot.* 62 (2011) 2411–2417.
- [73] I. Lager, L.L. Looger, M. Hilpert, S. Lalonde, W.B. Frommer, Conversion of a putative Agrobacterium sugar-binding protein into a FRET sensor with high selectivity for sucrose, *J. Biol. Chem.* 281 (2006) 30875–30883.
- [74] M. Sadoine, M. Reger, K.M. Wong, W.B. Frommer, Affinity series of genetically encoded forster resonance energy-transfer sensors for sucrose, *ACS Sens.* 6 (2021) 1779–1784.
- [75] Y.J. Wong, Y. Luo, X.J. Loh, X. Chen, Nondestructive sensing of plant-borne chemicals: biomarkers, agrochemicals, and pollutants, *Anal. Sens.* 5 (2025) e202500037.
- [76] T.C. Bang, S. Husted, K.H. Laursen, D.P. Persson, J.K. Schjoerring, The molecular-physiological functions of mineral macronutrients and their consequences for deficiency symptoms in plants, *New Phytol.* 229 (2021) 2446–2469.
- [77] A. Bernhoft, A brief review on bioactive compounds in plants, *Bioactive Compounds in Plants-Benefits and Risks for Man and Animals* 50 (2010) 11–17.
- [78] A. Rigal, Q. Ma, S. Robert, Unraveling plant hormone signaling through the use of small molecules, *Front. Plant Sci.* 5 (2014) 373.
- [79] G. Arimura, T. Uemura, Cracking the plant VOC sensing code and its practical applications, *Trends Plant Sci.* (2025).
- [80] M. Sood, Reactive oxygen species (ROS): plant perspectives on oxidative signalling and biotic stress response, *Discover Plants* 2 (2025) 187.
- [81] M. Eskola, G. Kos, C.T. Elliott, J. Hájšlová, S. Mayar, R. Krška, Worldwide contamination of food-crops with mycotoxins: validity of the widely cited 'FAO estimate' of 25%, *Crit. Rev. Food Sci. Nutr.* 60 (2020) 2773–2789.
- [82] A.-K. Mahlein, Plant disease detection by imaging sensors—parallels and specific demands for precision agriculture and plant phenotyping, *Plant Dis.* 100 (2016) 241–251.
- [83] T.O. Hara, B. Singh, Electrochemical biosensors for detection of pesticides and heavy metal toxicants in water: recent trends and progress, *ACS ES&T Water* 1 (2021) 462–478.
- [84] S. Banerji, H. Horak, J. Torop, T. Huynh, Unravelling the secrets of plants: emerging wearable sensors for plants signals and physiology, *Advanced Sensor Research* 3 (2024) 2300023.
- [85] V. Paul, R. Pandey, K. Ramesh, R.C. Meena, Atomic absorption spectroscopy (AAS) for elemental analysis of plant samples, Manual of ICAR Sponsored Training Programme for Technical Staff of ICAR Institutes on "Physiological Techniques to Analyze the Impact of Climate Change on Crop Plants 84 (2017) 84–86.
- [86] K.M. Quigley, A.G. Althoff, G.L. Donati, Inductively coupled plasma optical emission spectrometry as a reference method for silicon estimation by near infrared spectroscopy and potential application to global-scale studies of plant chemistry, *Microchem. J.* 129 (2016) 231–235.
- [87] N.T. Basta, M.A. Tabatabai, Determination of total potassium, sodium, calcium, and magnesium in plant materials by ion chromatography, *Soil Sci. Soc. Am. J.* 49 (1985) 76–81.
- [88] J.P. Giraldo, H. Wu, G.M. Newkirk, S. Kruss, Nanobiotechnology approaches for engineering smart plant sensors, *Nat. Nanotechnol.* 14 (2019) 541–553.
- [89] J.M. Buriak, L.M. Liz-Marzán, W.J. Parak, X. Chen, Nano and plants, *ACS Nano* 16 (2022) 1681–1684.
- [90] D. Zermas, D. Teng, P. Stanitsas, M. Bazakos, D. Kaiser, V. Morellas, D. Mulla, N. Papanikolopoulos, Automation solutions for the evaluation of plant health in corn fields, in: 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE, 2015, pp. 6521–6527.
- [91] C. Axelsson, A.K. Skidmore, M. Schlerf, A. Fauzi, W. Verhoef, Hyperspectral analysis of mangrove foliar chemistry using PLSR and support vector regression, *Int. J. Rem. Sens.* 34 (2013) 1724–1743.
- [92] G.S. Montanha, E.S. Rodrigues, J.P.R. Marques, E. Almeida, A.R. Reis, H. Pereira de Carvalho, X-ray fluorescence spectroscopy (XRF) applied to plant science: challenges towards in vivo analysis of plants, *Metallomics* 12 (2020) 183–192.
- [93] M. Zheng, T. Sheng, J. Yu, Z. Gu, C. Xu, Microneedle biomedical devices, *Nat. Rev. Bioeng.* 2 (2024) 324–342.
- [94] Q. Wang, Á. Molinero-Fernández, Q. Wei, X. Xuan, Á. Konradsson-Geuken, M. Cuartero, G.A. Crespo, Intradermal lactate monitoring based on a microneedle sensor patch for enhanced in vivo accuracy, *ACS Sens.* 9 (2024) 3115–3125, <https://doi.org/10.1021/acssensors.4c00337>.
- [95] Q. Wang, Á. Molinero-Fernández, A. Casanova, J. Titulaer, J.C. Campillo-Brocal, Á. Konradsson-Geuken, G.A. Crespo, M. Cuartero, Intradermal Glycine detection with a wearable microneedle biosensor: the first in Vivo Assay, *Anal. Chem.* 94 (2022) 11856–11864, <https://doi.org/10.1021/acs.analchem.2c02317>.
- [96] Á. Molinero-Fernández, A. Casanova, Q. Wang, M. Cuartero, G.A. Crespo, In vivo transdermal multi-ion monitoring with a potentiometric microneedle-based sensor patch, *ACS Sens.* 8 (2023) 158–166, <https://doi.org/10.1021/acssensors.2c01907>.
- [97] Á. Molinero-Fernández, Q. Wang, X. Xuan, Á. Konradsson-Geuken, G.A. Crespo, M. Cuartero, Demonstrating the analytical potential of a wearable microneedle-based device for intradermal CO₂ detection, *ACS Sens.* 9 (2024) 361–370.
- [98] X. Hui, Á. Molinero-Fernández, R. Zapata-Pérez, Y. Chen, M. Cuartero, G. A. Crespo, Implementation of sterilization and disinfection protocols for Potentiometric microneedle sensors: a requirement for a safety assertion, *ACS Sens.* (2026), <https://doi.org/10.1021/acssensors.5c04039>.
- [99] K.A. Grabowiecki, M. Majewski, T. Dylak, M. Gajewski, FEM modeling of the microneedle insertion into a cellular structure for microsampling of plant fluids, *Int. J. Biomater.* 2026 (2026), <https://doi.org/10.1155/ijbm/5581942>.
- [100] L. Zhang, C. Zhu, J. Shi, Z. Zhou, D. Ge, Design of three-section microneedle towards low insertion force and high drug delivery amount using the finite element method, *Comput. Methods Biomech. Biomed. Eng.* 27 (2024) 156–166, <https://doi.org/10.1080/10255842.2023.2174019>.
- [101] S.P. Davis, B.J. Landis, Z.H. Adams, M.G. Allen, M.R. Prausnitz, Insertion of microneedles into skin: measurement and prediction of insertion force and needle fracture force, *J. Biomech.* 37 (2004) 1155–1163, <https://doi.org/10.1016/j.jbiomech.2003.12.010>.
- [102] N. Yolai, W. Shu, E.D. O'cearbhail, C. Modchang, A.N. Annaidh, Finite element analysis of polymeric microneedle insertion into skin, *Mater. Des.* 259 (2025) 114936, <https://doi.org/10.1016/j.matdes.2025.114936>.
- [103] J.J. García-Guzmán, C. Pérez-Ráfol, M. Cuartero, G.A. Crespo, Microneedle based electrochemical (Bio) sensing: towards decentralized and continuous health status monitoring, *TrAC, Trends Anal. Chem.* 135 (2021) 116148.
- [104] Q. Wei, Á. Molinero-Fernández, D. Rojas, Q. Wang, G. Crespo, M. Cuartero, 3D-Printed hollow microneedle potentiometric sensors. A modular approach, *ACS Sens.* 11 (2026) 6191–6202.
- [105] Q. Wei, D. Rojas, Q. Wang, R. Zapata-Pérez, X. Xuan, Á. Molinero-Fernández, G. A. Crespo, M. Cuartero, Wearable 3D-Printed microneedle sensor for intradermal temperature monitoring, *ACS Sens.* 10 (2025) 4027–4037, <https://doi.org/10.1021/acssensors.4c03681>.
- [106] D. Rojas, M. Cuartero, G.A. Crespo, Toward a disruptive "Click-and-Run" 3D printing concept for manufacturing epidermal wearable electrochemical sensors, *ACS Sens.* 10 (2025) 7183–7198, <https://doi.org/10.1021/acssensors.5c00682>.
- [107] I. Xenikakis, K. Tsongas, E.K. Tzimtzimis, C.K. Zacharis, N. Theodoroula, E. P. Kalogianni, E. Demiri, I.S. Vizirianakis, D. Tzetzis, D.G. Fatouros, Fabrication of hollow microneedles using liquid crystal display (LCD) vat polymerization 3D printing technology for transdermal macromolecular delivery, *Int. J. Pharm.* 597 (2021) 120303, <https://doi.org/10.1016/j.ijpharm.2021.120303>.
- [108] C.J.W. Bolton, O. Howells, G.J. Blayney, P.F. Eng, J.C. Birchall, B. Gualeni, K. Roberts, H. Ashraf, O.J. Guy, Hollow silicon microneedle fabrication using advanced plasma etch technologies for applications in transdermal drug delivery, *Lab Chip* 20 (2020) 2788–2795, <https://doi.org/10.1039/D0LC00567C>.
- [109] C.-X. Fan, Z. Wang, Z.-H. Wang, A.-W. Wang, Z.-Y. Wang, L. Huang, A microneedle sensor for in-vivo sodium ion detection in plants, *Anal. Chim. Acta* 1352 (2025) 343892.

- [110] N. Singh, Q. Zhang, W. Xu, S.A. Whitham, L. Dong, A Biohydrogel-Enabled microneedle sensor for in situ monitoring of reactive oxygen species in plants, *ACS Sens.* 10 (2025) 1797–1810.
- [111] A. Bukhamsin, A. Ait Lahcen, J. Oliveira Filho, S. Shetty, I. Blilou, J. Kosel, K. N. Salama, Minimally-invasive, real-time, non-destructive, species-independent phytohormone biosensor for precision farming, *Biosens. Bioelectron.* 214 (2022) 114515.
- [112] K.R. Choi, M.L. Honig, P. Bühlmann, Ion-Selective potentiometry with plasma-initiated covalent attachment of sensing membranes onto inert polymeric substrates and carbon solid contacts, *Anal. Chem.* 96 (2024) 4702–4708, <https://doi.org/10.1021/acs.analchem.4c00204>.
- [113] Y. Tang, S. Li, L. Hu, X. Sun, B. Zhang, W. Ji, L. Ma, W. Qian, A. Kang, D. Zhu, Hybrid Poly(AMPS-CS)-Au microneedle arrays to enrich metabolites from skin for early disease diagnosis, *Adv. Healthcare Mater.* 10 (2021), <https://doi.org/10.1002/adhm.202100764>.
- [114] B.L. Garrote, M. Vegas-García, E. Hedberg, F. Ribet, N. Roxhed, L. García-Carmona, A. Quijano-López, M. García-Pellicier, Wearable device for in-situ plant sap analysis: electrochemical lateral flow (eLF) for stress monitoring in living plants, *Biosens. Bioelectron.* (2025) 117550.
- [115] H. Chen, S. Zhou, J. Chen, J. Zhou, K. Fan, Y. Pan, J. Ping, An integrated plant glucose monitoring system based on microneedle-enabled electrochemical sensor, *Biosens. Bioelectron.* 248 (2024) 115964.
- [116] F.E. Erukainure, B.N. Johnson, D.B. Langston, A.K. Chandel, Additively manufactured *in planta* integrated microneedle–microfluidic sensing: nondestructive electrochemical tracking of glucose and water stress in agricultural crop plants, *ACS Sens.* 11 (2026) 6128–6145, <https://doi.org/10.1021/acssensors.6c01122>.
- [117] I. Atay, E. Yilgör, G. Neşer, T. Abbasiasl, M.B. Yagci, I. Yilgör, L. Beker, Critical role of surface properties in passive interstitial fluid extraction using polymeric hollow microneedles for wearable diagnostics, *Adv. Mater. Interfac.* 12 (2025), <https://doi.org/10.1002/admi.202500001>.
- [118] N. Kashaninejad, A. Munaz, H. Moghadas, S. Yadav, M. Umer, N.-T. Nguyen, Microneedle arrays for sampling and sensing skin interstitial fluid, *Chemosensors* 9 (2021) 83, <https://doi.org/10.3390/chemosensors9040083>.
- [119] T. Abbasiasl, F. Mirlou, H. Mirzajani, M.J. Bathaei, E. Istif, N. Shomalizadeh, R. E. Cebecioglu, E.E. Özkahraman, U.C. Yener, L. Beker, A wearable touch-activated device integrated with hollow microneedles for continuous sampling and sensing of dermal interstitial fluid, *Adv. Mater.* 36 (2024), <https://doi.org/10.1002/adma.202304704>.
- [120] T. Abbasiasl, S. Sarica, U.C. Yener, E. Yilgor, I. Yilgor, H. Ceylan Koydemir, E. Öztürk, L. Beker, A hydrophilic hollow microneedle platform for sampling interstitial fluid and on-site biomarker detection, *Adv. Mater. Technol.* 10 (2025), <https://doi.org/10.1002/admt.202500891>.
- [121] J.G. Turner, E. Lay, U. Jungwirth, V. Varenko, H.S. Gill, P. Estrela, H.S. Leese, 3D-Printed hollow microneedle-lateral flow devices for rapid blood-free detection of c-reactive protein and procalcitonin, *Adv. Mater. Technol.* 8 (2023), <https://doi.org/10.1002/admt.202300259>.
- [122] T. He, J. Wang, E. Chae, C. Lee, In situ plant sensors: toward Real-Time, high-resolution monitoring, *ACS Sens.* 10 (2025) 6275–6291.
- [123] Z. Wang, C. Fan, C. Chen, Z. Wang, L. Fan, B. Luo, X. Wang, L. Huang, Z. Wang, Low-drift microneedle ion-selective electrodes for in situ monitoring of Mg²⁺ in plants, *Anal. Chim. Acta* 1421 (2026) 346029, <https://doi.org/10.1016/j.aca.2026.346029>.
- [124] A. Bukhamsin, K. Moussi, R. Tao, G. Lubineau, I. Blilou, K.N. Salama, J. Kosel, Robust, long-term, and exceptionally sensitive microneedle-based bioimpedance sensor for precision farming, *Adv. Sci.* 8 (2021) 2101261.
- [125] M. Parrilla, A. Steijlen, R. Kerremans, J. Jacobs, L. Haan, J. Vreesse, Y.V.N. Géron, P. Clerx, R. Watts, K. Wael, Wearable platform based on 3D-printed solid microneedle potentiometric pH sensor for plant monitoring, *Chem. Eng. J.* 500 (2024) 157254.
- [126] J. Li, J. Zhao, J. Huang, M. Liu, S. Huang, Preparation and performance study of hydrogel microneedle sensors for in situ monitoring of potassium ions in rice plants, *Microchim. Acta* 193 (2026) 121, <https://doi.org/10.1007/s00604-026-07900-3>.
- [127] G. Rosati, P.B. Deroco, M.G. Bonando, G.G. Dalkiranis, K. Cordero-Edwards, G. Maroli, L.T. Kubota, O.N. Oliveira Jr., L.A.M. Saito, C. Carvalho Castro Silva, Introducing all-inkjet-printed microneedles for in-vivo biosensing, *Sci. Rep.* 14 (2024) 29975.
- [128] Q. Wang, Y. Liu, J.C. Campillo-Brocal, A. Jiménez-Quero, G.A. Crespo, M. Cuartero, Electrochemical biosensor for glycine detection in biological fluids, *Biosens. Bioelectron.* 182 (2021) 113154.
- [129] C. Zhang, X. Wu, S. Yao, Y. Shao, C. Zhang, S. Zhou, J. Ping, Y. Ying, An implantable and self-powered sensing System for the in vivo monitoring of dynamic H₂O₂ level in plants, *Engineering* (2024).
- [130] J. Yun, S. Park, N.W. Kim, J. Kang, S. Kim, W. Ryu, K-doped Co₃O₄-decorated microneedle clip for non-enzymatic glucose detection in plant health monitoring, *Sens. Actuators B Chem.* 435 (2025) 137600.
- [131] H. Kim, S. Park, J. Kim, J. Yun, S. Kim, W. Ryu, Cobalt oxide based microneedle sensor for direct detection of glucose from plant leaves, *Micro & Nano Manufacturing* 2 (2026), <https://doi.org/10.1007/s44374-026-00017-w>.
- [132] H. Li, C. Wang, X. Wang, P. Hou, B. Luo, P. Song, D. Pan, A. Li, L. Chen, Disposable stainless steel-based electrochemical microsensor for in vivo determination of indole-3-acetic acid in soybean seedlings, *Biosens. Bioelectron.* 126 (2019) 193–199.
- [133] S. Wu, W. Nakagawa, Y. Mori, S. Azhari, G. Méhes, Y. Nishina, T. Kawano, T. Miyake, A plant-insertable multi-enzyme biosensor for the real-time monitoring of stomatal sucrose uptake, *Biosens. Bioelectron.* (2025) 117674.
- [134] K.J.H. Read, P.J. Hudson, J. Monclova, H. Monteith, R. Polsky, D.T. Hanson, P. R. Miller, K. Seitz, Non-destructive monitoring of tissue-specific, irrigation responsive impedance signals in leaves using microneedles probes, *bioRxiv* (2025), 2025.03. 31.646420.
- [135] D.T. Hanson, P.R. Miller, R. Polsky, P.J. Hudson, K.J.H. Read, Microneedle-Based Electrical Impedance Sensor to Monitor Plant Water Status in Real Time, Google Patents, 2021.
- [136] E. Jeon, S. Baek, S. Choi, K.S. Park, J. Lee, Real-time monitoring of electroconductivity in plants with microscale needle probes, *Environ. Control. Biol.* 56 (2018) 131–135.
- [137] S. Han, W. Kim, H.J. Lee, R. Joyce, J. Lee, Continuous and real-time measurement of plant water potential using an AAO-based capacitive humidity sensor for irrigation control, *ACS Appl. Electron. Mater.* 4 (2022) 5922–5932.
- [138] L. Chen, X. Ding, Y. Dong, H. Chen, F. Gao, B. Cui, X. Zhao, H. Cui, X. Gu, Z. Zeng, Integration of catalytic hairpin assembly probes into microneedles for detection of microRNA in plants, *Sens. Actuators B Chem.* 404 (2024) 135277.
- [139] M. Venbrux, S. Crauwels, H. Rediers, Current and emerging trends in techniques for plant pathogen detection, *Front. Plant Sci.* 14 (2023) 1120968.
- [140] D. Chen, C. Wang, W. Chen, Y. Chen, J.X.J. Zhang, PVDF-Nafion nanomembranes coated microneedles for in vivo transcutaneous implantable glucose sensing, *Biosens. Bioelectron.* 74 (2015) 1047–1052, <https://doi.org/10.1016/j.bios.2015.07.036>.
- [141] S. Zhang, C. Xia, J. Wang, S. Chen, Y. Wang, S. Zhang, Z. Geng, K. Tang, A. Erdem, B. Zhu, Ready-to-Use OECT biosensor toward rapid and real-time protein detection in complex biological environments, *ACS Sens.* 10 (2025) 3369–3380.
- [142] S. Zhou, Y. Chino, T. Kasama, R. Miyake, S. Mitsuzawa, Y. Luan, N.B. Ahmad, H. Hibino, M. Takai, Biocompatible core-shell microneedle sensor filled with Zwitterionic polymer hydrogel for rapid continuous transdermal monitoring, *ACS Nano* 18 (2024) 26541–26559, <https://doi.org/10.1021/acsnano.4c02997>.
- [143] J. Liu, J. Liu, Y. Liang, J. Yang, Y. Lin, Y. Li, Microneedle-Based electrochemical array patch for ultra-antifouling and ultra-anti-interference monitoring of subcutaneous oxygen, *Anal. Chem.* 97 (2025) 373–381, <https://doi.org/10.1021/acs.analchem.4c04345>.
- [144] L. Gao, Y. Cho, R. Wang, Y. Yao, D. Zhang, Y. Wang, Y. Cheng, Y. Wang, Q. Ma, I. Duplessis, Broadly applicable hydrophilic additive enhances electrochemical transistor function, in: *Proceedings of the National Academy of Sciences*, 123, 2026 e2523877123.
- [145] A. Saha, Y. Mi, N. Glassmaker, A. Shakouri, M.A. Alam, In situ drift monitoring and calibration of field-deployed potentiometric sensors using temperature supervision, *ACS Sens.* 8 (2023) 2799–2808.
- [146] A. Wiolek, M. Parrilla, M. Cuartero, G.A. Crespo, Epidermal patch with glucose biosensor: pH and temperature correction toward more accurate sweat analysis during sport practice, *Anal. Chem.* 92 (2020) 10153–10161.
- [147] M. Orozco-Cardenas, C.A. Ryan, Hydrogen peroxide is generated systemically in plant leaves by wounding and systemin via the octadecanoid pathway, *Proc. Natl. Acad. Sci.* 96 (1999) 6553–6557, <https://doi.org/10.1073/pnas.96.11.6553>.
- [148] X. Yang, D. Huo, Y. Tian, X. Geng, L. Xu, D. Zhong, R. Zhou, S. Xu, Y. Zhang, L. Sun, AuNPs/GO/Pt microneedle electrochemical sensor for in situ monitoring of hydrogen peroxide in tomato stems in response to wounding stimulation, *Anal. Bioanal. Chem.* 417 (2025) 1067–1079, <https://doi.org/10.1007/s00216-024-05728-5>.
- [149] C. Zhao, J. Park, S.E. Root, Z. Bao, Skin-inspired soft bioelectronic materials, devices and systems, *Nat. Rev. Bioeng.* 2 (2024) 671–690.
- [150] C. Zhang, J. Kong, Z. Wang, C. Tu, Y. Li, D. Wu, H. Song, W. Zhao, S. Feng, Z. Guan, B. Ding, F. Chen, Origami-inspired highly stretchable and breathable 3D wearable sensors for in-situ and online monitoring of plant growth and microclimate, *Biosens. Bioelectron.* 259 (2024) 116379, <https://doi.org/10.1016/j.bios.2024.116379>.
- [151] K. Koch, H.-J. Ensikat, The hydrophobic coatings of plant surfaces: epicuticular wax crystals and their morphologies, crystallinity and molecular self-assembly, *Micron* 39 (2008) 759–772.
- [152] P. Teng, Y. Cai, X. Liu, Y. Tuo, S. Wu, Q. Wang, Y. Li, F. Zhang, S. Wang, Inspiration of plant-related adhesion for plant wearable sensor interface design, *Nanoscale* 17 (2025) 13057–13075.
- [153] Y. Sun, X. Wang, M. Tang, M.K. Melarkey, T. Lu, Y. Xiang, S. Chen, 3D printing of succulent-inspired microneedle array for enhanced tissue adhesion and controllable drug release, *Adv. Mater. Technol.* 9 (2024) 2400216.
- [154] M. Farzam, M. Beitollahpoor, N.S. Pesika, Nature-inspired directional microneedle structures for reversible gripping on skin and fibrous materials, *Adv. Eng. Mater.* 26 (2024) 2400149.
- [155] X. Zhang, G. Chen, L. Cai, Y. Wang, L. Sun, Y. Zhao, Bioinspired pagoda-like microneedle patches with strong fixation and homeostasis capabilities, *Chem. Eng. J.* 414 (2021) 128905.
- [156] Y. Li, W. Zhou, C. Liu, D. Geng, J. Dai, Y. Xie, S. Chen, T. Luo, Z. Shen, Fabrication and characteristic of flexible dry bioelectrodes with microstructures inspired by golden margined century plant leaf, *Sens. Actuators A Phys.* 321 (2021) 112397.
- [157] G. Lohaus, M. Schwerdtfeger, Comparison of sugars, iridoid glycosides and amino acids in nectar and phloem sap of *Maurandya barclayana*, *Lophospermum erubescens*, and *Brassica napus*, *PLoS One* 9 (2014) e87689.
- [158] X. Li, W. Shan, Y. Yang, D. Joralmón, Y. Zhu, Y. Chen, Y. Yuan, H. Xu, J. Rong, R. Dai, Limpet tooth-inspired painless microneedles fabricated by magnetic field-assisted 3D printing, *Adv. Funct. Mater.* 31 (2021) 2003725.

- [159] M. Sang, K. Kim, J. Shin, K.J. Yu, Ultra-thin flexible encapsulating materials for soft bio-integrated electronics, *Adv. Sci.* 9 (2022) 2202980.
- [160] T.P. Delaney, S. Uknes, B. Vernooij, L. Friedrich, K. Weymann, D. Negrotto, T. Gaffney, M. Gut-Rella, H. Kessmann, E. Ward, A central role of salicylic acid in plant disease resistance, *Science* 266 (1994) 1247–1250.
- [161] M. Khalvandi, A. Siosemardeh, E. Roohi, S. Keramati, Salicylic acid alleviated the effect of drought stress on photosynthetic characteristics and leaf protein pattern in winter wheat, *Heliyon* 7 (2021) e05908.
- [162] X. Chen, J.M. Buriak, M. Salanne, H. Xin 18, *ACS Nano*, 2024, pp. 32279–32282.
- [163] Q. Jiang, X. Zhao, T. Zhao, W. Li, J. Ye, X. Dong, X. Wang, Q. Liu, H. Ding, Z. Ye, A machine-learning-powered spectral-dominant multimodal soft wearable system for long-term and early-stage diagnosis of plant stresses, *Sci. Adv.* 11 (2025) eadw7279.
- [164] O. Hossain, Y. Wang, M. Li, B. Mativenga, S. Jamalzadegan, N. Mohammad, A. Velayati, A.D. Poonam, Q. Wei, A dual-functional needle-based VOC sensing platform for rapid vegetable phenotypic classification, *Biosens. Bioelectron.* 278 (2025) 117341.
- [165] G. Lee, O. Hossain, S. Jamalzadegan, Y. Liu, H. Wang, A.C. Saville, T. Shymanovich, R. Paul, D. Rotenberg, A.E. Whitfield, Abaxial leaf surface-mounted multimodal wearable sensor for continuous plant physiology monitoring, *Sci. Adv.* 9 (2023) eade2232.
- [166] W. Wu, Anti-Crosstalk materials and structural decoupling strategies for multimodal flexible sensors, *Adv. Funct. Mater.* (2025) e24222.
- [167] F. Meng, R. Duan, H. Yang, Q. Dai, Y. Zhang, J. Fu, Advances in plant species recognition mediated by root exudates: a review, *Plants* 14 (2025) 3076.
- [168] V.B. Koman, T.T.S. Lew, M.H. Wong, S.-Y. Kwak, J.P. Giraldo, M.S. Strano, Persistent drought monitoring using a microfluidic-printed electro-mechanical sensor of stomata *in planta*, *Lab Chip* 17 (2017) 4015–4024, <https://doi.org/10.1039/C7LC00930E>.
- [169] Q. Zhang, S. Ma, W. Meng, Y. Zheng, L. Yin, H. Wang, H. Shi, K. Zhang, S. Su, Smartphone-based plant-wearable microfluidic sensor with self driven electrolyte for in-situ detection of methyl parathion, *Sens. Actuators B Chem.* 418 (2024) 136254, <https://doi.org/10.1016/j.snb.2024.136254>.
- [170] W. Li, Y. Luo, P. Jiang, X. Dong, K. Tang, Z. Liang, Y. Shi, A sustainable crop protection through integrated technologies: UAV-based detection, real-time pesticide mixing, and adaptive spraying, *Sci. Rep.* 15 (2025) 35748.
- [171] L. Salvador-Carulla, C. Woods, C. Miquel, S. Lukersmith, Adaptation of the technology readiness levels for impact assessment in implementation sciences: the TRL-IS checklist, *Heliyon* 10 (2024) e29930.