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Journal of Plant Electrobiology
http://dx.doi.org/10.62762/JPE.2026.146822

REVIEW ARTICLE

Electrobiological Signatures as Early Indicators of Plant Stress and Adaptation

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Abstract

Plants, being sessile, must constantly monitor and respond to environmental fluctuations and stressors. Among the diverse signalling modalities (chemical, hydraulic, hormonal), electrical signals stand out for their rapid propagation and capacity to serve as early warning cues. In this review, we examine the concept of electrobiological signatures—distinctive patterns of electrical activity in plants as potential early indicators of stress and adaptation. This review first discusses the fundamental mechanisms such as ion fluxes, membrane transporters, coupling with calcium dynamics, reactive oxygen species (ROS), and cross-talk with hormonal networks. Next, it explores how these signatures manifest under abiotic and biotic stress and how these signatures are linked to downstream adaptive responses. Then, it shifts to agricultural applications, highlighting real-time plant monitoring, phenotyping, stress forecasting, and precision interventions. Finally, plant electrobiology is placed in an ecological context, considering how electrical signalling may mediate plant-plant communication, ecosystem resilience, and bioindication of environmental change. We emphasize that, despite technical and biological challenges such as signal noise, species variability, and decoding specificity, the integration of electrophysiological data with multi-omics approaches and AI analytics offers a promising pathway to transform plant monitoring and management. Therefore, while hurdles remain, the convergence of flexible sensors and AI positions electrobiological signatures as a transformative tool for 21st-century plant science.

Keywords: plant electrophysiology, ion fluxes, calcium signalling, abiotic stress, biotic stress, precision agriculture, real-time monitoring.

1 Introduction

Plants live in an ever-changing environment and, unlike motile animals, cannot relocate to avoid stress [1, 2]. To survive, they have evolved complex signalling networks chemical, hydraulic, hormonal, and electrical to detect perturbations (e.g. drought, pathogens, and temperature extremes) and to coordinate systemic responses [3]. Among these, electrical signaling offers a unique advantage: it can serve as an early indicator of plant stress and adaptation [4, 5]. Because electrical signals propagate faster than diffusion-based chemical signals, they are well-suited to serve as early warning

Submitted: 04 February 2026
Accepted: 27 March 2026
Published: 31 March 2026

Vol. 1, **No.** 1, 2026.
10.62762/JPE.2026.146822

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Citation
Javed, Q., & Azeem, A. (2026). Electrobiological Signatures as Early Indicators of Plant Stress and Adaptation. *Journal of Plant Electrobiology*, 1(1), 58–73.

systems within the plant [6].

Historically, the idea of electrical activity in plants dates back more than a century, with early studies by Stahlberg R. and others observing and movements in sensitive plants like *Mimosa pudica* L. [7]. Over time, plant electrophysiology has evolved from descriptive observations into a mechanistic discipline, identifying ion channels, pumps, and signalling cascades [8, 9]. Modern reviews emphasize that plants generate action potentials (AP), variation potentials (VP), and system potentials (SP), each differing in kinetics, propagation mode, and stimulus specificity [10, 11].

Electrical signals do not act in isolation. They often integrate with calcium waves, reactive oxygen species (ROS) signalling, pH changes, and hormonal cascades (e.g. jasmonates, abscisic acid) to effect physiological changes (e.g. stomatal closure, gene expression) [12]. Because of this, the term "electrobiological signature" can be used to denote the full dynamic pattern (amplitude, kinetics, frequency, spatial propagation) of electrical responses associated with a given stress or adaptive event [13]. In plant electrophysiology, the signal types AP, VP and SP, arise when stimuli perturb membrane ion gradients and generate propagating voltage transients. The combined features of these signals their waveforms, timing, spectral content, and propagation form stimulus-dependent electrical patterns that encode information about environmental conditions [14]. Recent studies show that such electrome patterns are classifiable: machine-learning analyses of bean plants, for example, can discriminate water-stress states with high accuracy before visible symptoms appear [15, 16]. Together, these findings support the view that coordinated electrical dynamics constitute reproducible electrophysiological fingerprints of specific stresses and adaptive responses rather than random fluctuations [14].

In the context of plant stress and adaptation, such electrobiological signatures are promising for several reasons such as electrical changes can precede visible symptoms and large-scale biochemical alterations, they offer an early warning window for timely intervention [17–19]. Moreover, differences in the shape, timing, and frequency of electrical responses may encode information about both the type and severity of stress such as drought, salinity, or pathogen attack [20, 21]. Taken together, these findings support the emerging view that plant electrical signals can function as measurable physiological indicators of environmental stress. However, translating these signals from experimental observations into practical tools requires improved signal detection, reliable interpretation, and scalable monitoring technologies. In this context, the integration of high-resolution electrophysiological measurements with sensor networks and advanced data-analysis approaches (including machine learning) represents a key pathway for converting plant electrical dynamics into actionable indicators for crop management and ecosystem monitoring [22, 23]. Finally, because electrical activity can be recorded continuously using electrodes or sensor networks, these signals are well suited for real-time monitoring and scalable deployment, opening the door to field-level diagnostics of plant health and resilience [24, 25].

Beyond agriculture, electrical signalling may mediate plant-plant communication in ecological settings [26, 27]. However, several key factors remain, including signal noise, species-specific variability, environmental interference, and the challenge of linking particular electrical patterns to specific stressors [28]. This review aims to bridge theory and application by first surveying the fundamental mechanisms underlying plant electrical signalling through different case studies [29–33]. It then examines how electrobiological signatures change under stress and how they may contribute to adaptive responses. Special attention is given to current technological and analytical advances that may help overcome existing limitations and enable the practical use of plant electrical signals in agriculture and ecosystem monitoring. Finally, current limitations and future research directions are assessed in order to advance the development of electrical signatures as practical tools in plant science.

2 Fundamentals of Plant Electrobiology

2.1 Electrical Phenomena in Plants

Plants, despite lacking a nervous system, exhibit complex electrical activities that play crucial roles in their perception of environmental stimuli, signal transduction, and systemic coordination of physiological responses [34, 35]. The resting membrane potential in plant cells is typically negative, established and maintained by the differential distribution of ions across the plasma membrane. Key contributors include the H^+-ATPase, which pumps protons out of the cell, and selective K^+ channels that regulate potassium flux. Depolarization occurs when cations such as Ca^{2+} or Na^+ enter the cell, reducing the negative potential, and repolarization follows as K^+ efflux restores the membrane to its resting state. These changes in membrane potential form the foundation for the generation and propagation of electrical signals in plants [9, 36].

Plants generate several distinct types of electrical signals (discrete events such as AP and VP which arise from the broader electrical activity of tissues. These signals, when analyzed collectively, form electrobiological signatures that encode information about the type, intensity, and location of stressors) that vary in speed, amplitude, and range of propagation. AP are rapid, all-or-nothing responses characterized by a swift depolarization followed by repolarization, commonly observed in specialized cells such as those of the Dionaea muscipula J. Ellis (Venus flytrap) [37]. AP allow plants to react quickly to mechanical stimuli, triggering rapid movements or immediate cellular responses [29]. In contrast, VP are typically induced by wounding, mechanical damage, or severe environmental stress and differ mechanistically from APs. Rather than being self-propagating electrical impulses, VPs are generally considered electrical responses triggered by hydraulic pressure changes and chemical signals (such as ROS) generated at the site of injury. These hydraulic and chemical cues propagate through vascular tissues and subsequently induce membrane depolarization in distal cells. As a result, VPs usually display slower and more variable electrical profiles compared with APs and are closely associated with the activation of systemic defense pathways [29, 38–40]. While SP represent another category of long-distance electrical signals that transmit transient changes across the plant, coordinating systemic responses such as gene expression and hormonal regulation in distal tissues [41].

The generation and propagation of these electrical signals are intimately tied to the fluxes of ions such as Ca^{2+}, K^+, Cl^-, and H^+ across the plasma membrane [8]. Calcium ions serve as pivotal secondary messengers, coupling electrical events to downstream biochemical and transcriptional responses, whereas potassium flux contributes to repolarization and maintenance of turgor [42]. Chloride ions help maintain charge balance during ion movement, and H^+-ATPase activity establishes a proton gradient that underpins the resting potential and intracellular pH homeostasis [43, 44]. The interplay of these ions enables plants to encode information about the type, intensity, and location of stressors within their bioelectrical patterns [45].

Electrical signalling in plants is not isolated but tightly integrated with hormonal and reactive oxygen species (ROS) signalling pathways [46, 47]. Electrical changes can trigger the production of jasmonic acid, ethylene, abscisic acid, and other phytohormones, linking early electrical perception to systemic defense responses [41]. Concurrently, fluctuations in membrane potential often lead to controlled ROS bursts, which act as signalling molecules to regulate gene expression and reinforce stress adaptation. This integration allows plants to coordinate rapid, multilevel responses to both biotic and abiotic challenges, enhancing their survival in dynamic environments [21, 48]. Recent studies have emphasized that these bioelectrical signatures distinctive combinations of amplitude, duration, and propagation patterns carry specific information about stress type and severity, effectively functioning as an early-warning system within the plant [49].

2.2 Mechanisms of Signal Propagation and Integration

Electrical signals in plants are not confined to the cells where they originate; rather, they propagate across tissues and organs, coordinating systemic responses to environmental cues and stressors [26]. Signal propagation in plants involves a combination of electrical, chemical, and hydraulic mechanisms that together enable rapid communication over long distances [46]. Unlike animals, plants rely on non-neuronal pathways, with phloem, plasmodesmata, and the apoplast serving as the primary conduits for electrical and chemical signal transmission [35].

Long-distance propagation of electrical signals is facilitated by structural features of plant tissues. The phloem, with its sieve elements and companion cells, provides a low-resistance pathway for the rapid movement of ions and small signalling molecules [50]. Plasmodesmata allow intercellular coupling, enabling both electrical and chemical continuity across tissues [51]. The xylem, while primarily serving water transport, contributes to VP propagation through hydraulic pressure changes that can trigger depolarizations in adjacent cells [52]. Additionally, recent studies suggest that systemic signals can move through mycorrhizal networks or root contacts between neighbouring plants, implying that electrical and chemical signals extend beyond individual organisms to influence community-level responses [53–55].

Experimental evidence also highlights the importance of signal specificity in electrical propagation. Different stressors generate distinct electrical signatures in terms of amplitude, duration, and frequency [56]. For example, AP induced by mechanical touch are typically brief and uniform, whereas VP induced by wounding show slower onset and variable amplitude. These differences allow plants to discriminate between stimuli and activate appropriate downstream responses [29, 57]. Advances in high-resolution electrophysiology, combined with imaging of Ca^{2+} and ROS dynamics, have provided detailed insights into how these electrical patterns are decoded by cellular signalling networks, demonstrating the sophistication of plant information processing in the absence of neurons [58, 59].

Integration of electrical signalling with environmental perception underscores its adaptive value. Electrical responses allow plants to anticipate and prepare for stress before visible damage occurs, enabling early activation of defense mechanisms, stomatal regulation, and metabolic adjustments [12]. At the cellular level, membrane depolarization triggered by electrical events often induces Ca^{2+} influx through voltage-dependent channels, generating cytosolic Ca^{2+} spikes that function as secondary messengers. These Ca^{2+} signals can activate calcium-dependent protein kinases (CDPKs) and related signalling components, which in turn regulate downstream transcriptional responses. In the context of wounding or herbivory, such Ca^{2+}-dependent pathways contribute to the activation of jasmonic acid biosynthesis and the regulation of transcription factors such as MYC2, thereby linking early electrical perception to systemic defense responses in distal tissues.

This rapid communication system is particularly advantageous under fluctuating environmental conditions, such as drought, salinity, herbivory, or pathogen attack, where timely systemic responses can determine survival [60]. Furthermore, the combination of electrical, chemical, and hydraulic signalling provides redundancy and robustness, ensuring that critical information reaches target tissues efficiently even if one pathway is compromised [4, 61]. The coordination of electrical signals with Ca^{2+} waves, ROS bursts, and hormone signalling therefore forms a multi-layered regulatory network that enables plants to translate early bioelectrical cues into appropriate physiological and transcriptional adaptations. Understanding these mechanisms provides critical insights into plant stress perception, signalling fidelity, and resilience, highlighting the sophisticated electrobiological capacities of plants in responding to dynamic environmental challenges.

2.3 Techniques for Measuring Electrobiological Signatures

The study of plant bioelectrical activity has evolved significantly, with advancements in both traditional and modern measurement techniques enhancing our understanding of plant signalling [33, 62]. Traditional electrophysiological methods, such as microelectrodes and patch-clamp techniques, have been foundational in characterizing plant membrane potentials and ion channel activities [9]. Microelectrodes, typically glass pipettes filled with conductive solutions, allow for precise measurements of intracellular and extracellular potentials. These tools have been instrumental in studying rapid electrical responses like action potentials in specialized plant cells [33, 63].

In recent years, modern tools have emerged, offering more versatile approaches to monitor plant electrical activity. Extracellular electrodes, such as microelectrode arrays (MEAs), enable the simultaneous recording of electrical signals from multiple plant cells or tissues [13]. For instance, a 3D helical MEA has been developed to facilitate in vitro extracellular action potential recordings, providing insights into the dynamic electrical responses of plant cells [64]. These MEAs are particularly useful for studying long-distance electrical signalling and the effects of various stimuli on plant bioelectrical activity [62]. Biosensors have also become pivotal in measuring plant electrobiological signatures. These devices can detect specific biochemical changes associated with electrical activity, offering a complementary approach to traditional electrophysiology [65]. For example, wearable electrochemical sensors have been designed to monitor plant small molecules, such as phytohormones and metabolites, which are often involved in electrical signalling pathways [66]. These sensors are typically flexible and can be directly applied to plant surfaces, allowing for real-time, in situ monitoring of plant physiological states [67].

Impedance spectroscopy is another modern technique employed to assess plant electrical properties. By applying a small alternating current and measuring the resulting voltage, impedance spectroscopy provides information about the resistive and capacitive characteristics of plant tissues [68]. This method is particularly effective in detecting changes in plant health and stress responses, as alterations in tissue impedance often correlate with physiological changes [69].

Data acquisition and analysis play crucial roles in interpreting electrobiological measurements. Signal filtering techniques are employed to remove noise and artifacts from raw data, ensuring the accuracy of measurements [70]. Advanced computational methods, including machine learning and pattern recognition approaches, have been increasingly applied to analyze complex datasets. These techniques enable the identification of patterns and correlations within large volumes of data, facilitating the development of predictive models for plant responses to various stimuli [71]. Moreover, the more information about the instruments and sensors used for measuring electrobiological signatures in plants has been added in Table 1 and Figure 1.

3 Electrobiological Responses to Plant Stress

3.1 Abiotic Stresses

Plants respond to a wide range of abiotic stressors, such as drought, salinity, temperature extremes, light stress, and heavy metal exposure, through measurable changes in their bioelectrical activity [82]. Under drought and salinity stress, membrane potentials are significantly modulated, primarily through the activation or inhibition of ion channels such as K^+, Ca^{2+} , and Cl^- channels [45]. These ionic fluxes not only help maintain turgor and osmotic balance but also act as early indicators of stress perception. For example, *Arabidopsis thaliana* and *Oryza sativa* exhibit rapid depolarization events under salinity stress, with associated calcium waves that coordinate adaptive responses, including stomatal closure and osmoregulatory synthesis [83, 84].

Temperature extremes, both heat and cold, trigger VP that propagate through plant tissues. These thermally induced electrical signals serve adaptive roles by preconditioning cells to stress, often priming heat-shock or cold-responsive genes before visible damage occurs [85]. In *Solanum lycopersicum*, high-temperature-induced depolarizations were shown to activate ROS signalling, enhancing tolerance to subsequent heat stress [86]. Similarly, low-temperature stress in *Arabidopsis* triggers long-distance calcium-mediated electrical waves that activate antifreeze proteins in distal tissues [87].

Light stress and UV radiation can also influence plant electrical activity. Photoreceptors such as phytochromes and cryptochromes are linked to transient electrical changes, modulating membrane potentials and downstream hormone signalling pathways [88]. In *Cucumis sativus* L. (cucumber), exposure to high-intensity UV-B radiation induced hyperpolarization events correlated with enhanced production of flavonoids, serving as protective metabolites [89]. Heavy metals and pollutants disrupt ionic homeostasis, leading to measurable bioelectric imbalance [90]. Studies in *Aegiceras corniculatum* (L.) Blanco and *Kandelia obovata* demonstrated that salinity combined with metal stress altered both voltage amplitude and frequency in root tissues, suggesting electrophysiological signatures can serve as early biomarkers of environmental toxicity [91, 92].

3.2 Biotic Stresses

Biotic stresses, including herbivore, pathogen attack, and mechanical wounding, elicit rapid electrical responses in plants, often functioning as the first layer of defense [3, 93]. For instance, when *Nicotiana tabacum* L. is mechanically wounded or attacked by herbivores, AP and VP propagate from the local damage site to distal tissues, activating jasmonic acid and salicylic acid signalling pathways [94]. In addition, ROS bursts linked with electrical signalling reinforce systemic acquired resistance and prime neighbouring cells for defense [46]. Electrical signalling also mediates systemic coordination, linking local perception to whole-plant responses. In barley, studies using extracellular electrodes and wearable sensors demonstrated that local leaf wounding generates a cascade of electrical signals that trigger defensive metabolite accumulation in distant leaves within minutes [95]. Similarly, pathogen attack in *Arabidopsis* induces specific voltage oscillations that correlate with calcium and ROS waves, effectively coordinating localized and systemic defense responses [96].

3.3 Stress-Specific Electrobiological Signatures

Distinct electrobiological signatures have been identified for different stressors, often characterized by unique voltage patterns, frequency changes, or signal duration. These signatures allow for early detection of stress before visible phenotypic changes occur [97]. However, it is important to emphasize that the concept of fully stress-specific signatures remains provisional. Significant overlap exists among responses—for example, both wounding and heat can trigger variation potentials (VPs). Signal measurements are also affected by biological factors such as plant age,

Table 1. Instruments and sensors used for measuring electrobiological signatures in plants.

Technique / Method	Main Instruments & Sensors	Measured Parameter / Signal Type	Applications in Plant & Rhizosphere Studies	References
Surface Electrode Recording	Ag/AgCl or Pt electrodes; differential amplifier (e.g., Lab-Trax 4/24T, WPI); data acquisition software (e.g., LabScribe v3); shielded cables and Faraday cage	Surface potential changes, action potentials, variation potentials	Monitoring electrical responses of leaves, stems, or roots to drought, salinity, light, and mechanical or pollutant stress	[72]
Microelectrode (Intracellular) Recording	Glass capillary microelectrodes (KCl-filled), high-impedance amplifier, micromanipulator, oscilloscope	Membrane potential, ion channel activity	Recording cellular potentials in root hairs, guard cells, or mesophyll; studying ion transport and stress physiology	[73]
Multielectrode Array (MEA)	Planar multichannel electrode array or flexible organic array; amplifier; multichannel recorder	Spatial propagation of bioelectric signals	Mapping electrical activity in leaves or roots; studying long-distance signalling and systemic responses	[13]
Scanning Ion-Selective Electrode Technique (SIET)	Ion-selective microelectrodes (H^+, K^+, Ca^{2+}); micropositioner; ion flux measurement system (e.g., NMT system, YoungerUSA)	Ion flux near root or rhizosphere surface	Measuring nutrient uptake, efflux, and rhizosphere acidification; assessing ion homeostasis under metal or salt stress	[74]
Scanning Electrochemical Microscopy (SECM)	Ultramicroelectrode (Pt or carbon); piezo scanner; potentiostat; electrochemical workstation	Local redox and electrochemical activity	Mapping oxygen, ROS, and redox gradients around roots or leaves; detecting pollutant effects	[75]
Bioimpedance Spectroscopy (BIS)	Impedance analyzer (e.g., Agilent 4294A, Hioki IM3570); electrode clips or flexible films	Electrical impedance, capacitance, conductivity	Estimating water status, tissue integrity, xylem function, and root vitality under stress	[76]
Voltage-Sensitive Dye Imaging (VSDI)	Voltage-sensitive fluorescent dyes (e.g., Di-8-ANEPPS); fluorescence microscope; CCD camera	Optical voltage imaging	Visualizing electrical waves and propagation through leaves and stems; studying heat or light-induced potentials	[77]
Organic Electrochemical Transistors (OECTs)	PEDOT:PSS-based organic transistor; flexible polymer substrate; source–drain–gate amplifier circuit	Amplified bioelectric potential	High-resolution electrophysiology of leaves and traps; integration with IoT biosensing systems	[78]
Wearable Bioelectronic Sensors	Graphene oxide or PEDOT:PSS flexible electrodes; adhesive conductive film; wireless data logger	Electrical potential, impedance, humidity, and temperature	Continuous monitoring of plant physiological states and stress in field conditions	[79]
Plant Electrophysiological Sensor Networks	Embedded microelectrode arrays; environmental sensors (moisture, temperature); wireless IoT node	Real-time voltage patterns correlated with environmental factors	Field-scale monitoring of plant responses to drought, salinity, and pollution; smart-agriculture integration	[80]
Integrated Physiological Platforms	Combined electrical amplifier, turgor pressure probe, IRGA (gas exchange), temperature sensors	Electrical potential with physiological metrics	Studying linkages between electrical signalling, transpiration, and gas exchange	[81]

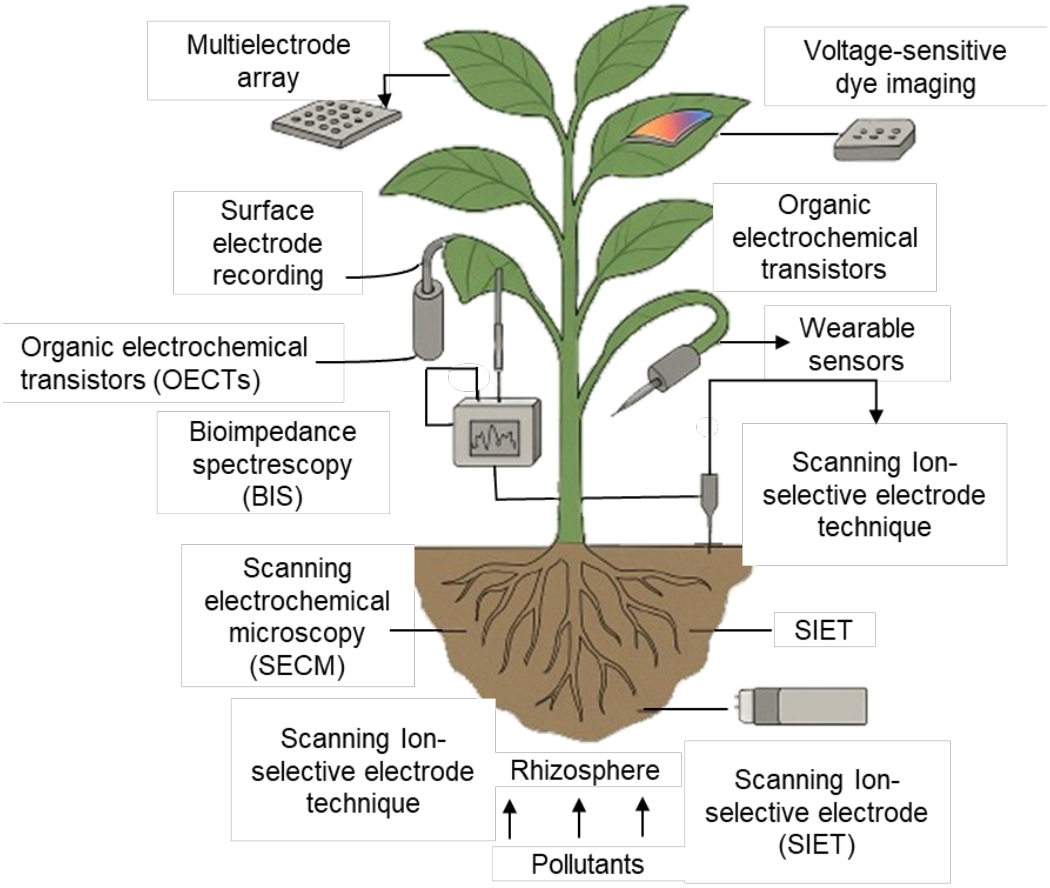

Figure 1. Overview of instruments and sensors used to record plant electrobiological signals. Different devices, including microelectrodes, patch-clamp setups, multielectrode arrays (MEAs), and wearable plant sensors, are depicted along with the plant compartments they monitor: roots, shoots, leaves, and the rhizosphere. This schematic illustrates the spatial coverage of different technologies and their associations with specific physiological processes, providing a conceptual framework for linking sensor placement to plant bioelectrical measurements.

circadian rhythms, and nutritional status, as well as technical challenges including noise, electrode placement, and environmental variability. Therefore, while Table 2 summarizes reported patterns, these should not be interpreted as a definitive 'dictionary' of stress signatures. Instead, they represent emerging trends that require further validation under controlled and field conditions.

Electrobiological measurements are generally complemented by Ca^{2+} imaging or ROS detection to link electrical changes with physiological adaptation, but careful interpretation is required given the high variability and context-dependence of these signals.

4 Agricultural Applications

4.1 Electrophysiological Monitoring for Precision Agriculture

Plant bioelectrical signals have moved from curiosity to practical sensors in precision agriculture. Several recent studies demonstrate that real-time electrical monitoring can provide earlier stress detection than traditional point-based measures [107–109]. For example, custom greenhouse-capable electrophysiological sensors enable continuous, real-time recording of plant electrical activity in production settings without requiring a Faraday cage, showing clear signal changes under water and salt stress [110]. High-density, conformable multielectrode arrays (MEAs) allow spatially resolved mapping of electrical activity across organs and whole plants. These arrays improve signal-to-noise, enable simultaneous multi-site monitoring, and scale toward field-deployable systems. MEA recordings reveal stress-specific spatiotemporal patterns, such as oscillation frequency shifts or baseline depolarization changes, which can be extracted and analyzed via feature-engineered time-series pipelines [111].

For example, Cattani et al. [112] demonstrated that a specific impedance metric measured in grapevine

Table 2. Plant stress responses and their characteristic electrobiological signatures.

Stress Type	Plant Species / Model	Electrobiological Response	Signal Characteristics	Physiological / Adaptive Role	References	Detection Methods
Drought	*Zea mays* L. (maize)	Depolarization in root and leaf cells	Gradual depolarization, oscillatory high-frequency spikes	Activation of ABA signalling, stomatal closure, osmotic adjustment	[98]	Extracellular voltage recording, impedance measurement
Salinity	*Glycine max* (L.) Merr. (soybean)	Membrane hyperpolarization followed by calcium waves	Transient hyperpolarization, Ca^{2+} spike propagation	Ion homeostasis maintenance, salt tolerance	[99]	Electrophysiological recording, confocal fluorescence microscopy
Heat stress	*Brassica napus* L. (canola/rapeseed)	Rapid variation potentials in leaves	Short-duration depolarization, high amplitude	ROS signalling activation, heat-shock protein induction	[100]	VP measurement, temperature correlation analysis
Cold stress	*Oryza sativa* L. (rice)	Long-distance calcium-mediated electrical waves	Slow, long-duration depolarization with periodic oscillations	Priming of antifreeze protein expression	[87, 101]	Long-distance Ca^{2+} wave detection, optical mapping
High UV / Light stress	*Spinacia oleracea* L. (spinach)	Hyperpolarization in mesophyll cells	Repetitive hyperpolarization events, moderate amplitude	Induction of flavonoid synthesis and photoprotective metabolites	[102]	Membrane potential monitoring, fluorescence spectroscopy
Heavy metal (Cd, Pb)	*Aloe vera* (L.) Burm. f.	Irregular voltage spikes in roots	Variable amplitude and duration, irregular frequency	Early indicator of metal stress, disruption of ionic transport	[103]	Electrical activity mapping, ion concentration monitoring
Herbivory / Wounding	*Nicotiana tabacum* L.	Local APs and VPs propagate to distal leaves	Rapid AP (milliseconds) followed by slower VP (seconds–minutes)	Activation of JA/SA pathways, systemic defense	[48, 104]	AP tracing, mechanical wounding response recording
Pathogen attack	*Arabidopsis thaliana* (L.) Heynh.	Oscillatory voltage changes linked to Ca^{2+} waves	Low-frequency oscillations, repetitive spikes	Systemic acquired resistance, ROS signalling	[105]	Oscillatory voltage analysis, Ca^{2+} wave correlation mapping
Mechanical touch	*Mimosa pudica* L.	Rapid AP triggering leaf movement	Large amplitude, all-or-none AP	Immediate defensive movement, avoidance behaviour	[106]	Rapid AP detection, time-resolved electrophysiology

AP = Action Potential; VP = Variation Potential

Signals are often stress-specific in amplitude, duration, frequency, and propagation distance.

Electrobiological measurements are generally complemented by Ca^{2+} imaging or ROS detection to link electrical changes with physiological adaptation.

Electrical signals = AP, VP, SWP

Electrobiological signature = pattern of multiple signals over timeElectrical activity = continuous bioelectrical fluctuations stems correlates strongly with stem water potential, enabling continuous water-status monitoring and the potential for closed-loop precision irrigation. Changes in baseline potential, oscillation frequency, and transient depolarization events were used as indicators, processed through filtering, feature extraction, and correlation with environmental and physiological metrics.

Through IoT integration and edge/cloud analytics, low-cost, wireless electrophysiology sensor nodes and wearable plant sensors allow electrical signals to be streamed, aggregated, and fed into cloud AI for trend detection and forecasting. Several prototype systems and reviews describe architectures for wireless EP-sensor networks suitable for greenhouses and urban agriculture [113]. Moreover, supervised and deep-learning pipelines applied to time-series electrical data have successfully classified infection and nutrient-deficit states, showing promise for early detection of viral or fungal infections before visible symptoms appear [114, 115]. Taken together, these advances illustrate feasible near-term systems in which plant electrophysiology can be directly integrated into precision-agriculture decision loops. Plants act as self-reporting biosensors, feeding live status information including baseline potentials, oscillation patterns, and transient spikes into irrigation controllers, nutrient schedulers, or warning dashboards [110].

4.2 Sustainable Farming and Pesticide Reduction

Electrophysiological monitoring supports sustainability goals by enabling earlier detection of sublethal stress and more targeted management, which potentially reduce unnecessary applications of water, fertilizer, and pesticides. Continuous electrical monitoring allows farmers to identify localized onset of stress (e.g., water deficit or nutrient limitation) and apply inputs only where and when needed. Proof-of-concept studies in vineyards and greenhouse crops have shown that EP-derived alerts can reduce sampling frequency and enable more precise irrigation scheduling [112]. Machine-learning analyses of plant electrical signatures have shown promise for early detection of viral and other infections, which could, in principle, allow more targeted interventions. However, it is important to note that deploying sprayers or treatment systems with the spatial and temporal precision required to act on single-plant or small-cluster signals in open-field conditions remains a major engineering and economic challenge. Current technologies are primarily at the proof-of-concept stage, and widespread field implementation would require advances in sensor coverage, automated actuation, and cost-effective integration with farm management systems [116–119].

Advances in flexible and wearable plant sensors improve biocompatibility and scalability; these devices can be deployed across canopies to produce high-resolution physiological maps. Such maps could inform variable-rate application strategies (fertigation, spot-spraying) at a broader scale, though full plant- or row-specific precision is not yet feasible. Reviews of wearable plant sensor technology outline progress and the remaining engineering challenges for large-scale adoption [117]. Overall, electrophysiological monitoring contributes to sustainable farming primarily by enhancing early detection and providing actionable information for informed decision-making, while the practical realization of highly targeted pesticide application remains a future goal rather than a current capability.

5 Environmental and Ecological Implications

Electrobiological signalling is increasingly recognized as a mechanism for rapid systemic coordination within individual plants and, in some cases, between neighbouring plants. VP and slow electrical waves triggered by mechanical, herbivore, or abiotic stress can induce systemic responses such as defense priming and stomatal adjustments [60]. Empirical studies show that repeated or chronic stress can modify a plant's baseline electrical activity, indicating stress memory and providing potential bioelectric markers for physiological status [60, 112, 120].

In natural ecosystems, there is evidence for coordinated electrophysiological responses to environmental perturbations such as episodic drought, heat, and salinity pulses. Long-distance AP and VP propagation has been shown to regulate stomatal conductance, photosynthesis, and hydraulic adjustments in distal tissues, illustrating functional consequences of electrical signalling under stress [12, 120]. Chronic stress can shift baseline membrane potentials or oscillation patterns, offering a measurable indicator of plant health at both individual and population scales.

Portable electrophysiological loggers and sensor networks allow continuous tracking of plant responses to environmental fluctuations (e.g., water availability, temperature anomalies, or pollutants). Because electrical signals integrate whole-plant physiological status, they provide biologically meaningful proxies that complement traditional abiotic sensors, and could serve as bioindicators for monitoring ecosystem health. For example, studies in grapevines and greenhouse crops demonstrated correlations between electrical activity and water deficit or nutrient limitation [112].

Electrical activity also interacts with rhizosphere processes. Root-borne potentials can influence redox gradients and microbial community composition, linking plant electrophysiology with nutrient cycling and soil function. While direct whole-ecosystem evidence remains limited, these mechanistic insights suggest that monitoring plant electrobiological signals may offer a sensitive approach to detect early or chronic stress, supporting ecosystem monitoring efforts without overextending claims about resilience.

6 Challenges and Future Perspectives

Despite advances in flexible electrodes, high-impedance amplifiers, and wireless sensors, several challenges remain for the field deployment and interpretation of plant electrophysiological data:

- Signal noise and environmental interference remain major obstacles. Motion artifacts caused by growth, wind, or handling, as well as baseline drift over hours to days, complicate data acquisition in real-world settings. Advanced signal-processing approaches including wavelet transforms, adaptive filtering, and machine-learning–based denoising are increasingly required to extract meaningful physiological information from raw electrical traces. Species-specific differences in tissue impedance and anatomy further complicate cross-system comparisons. Studies have highlighted mechanistic differences between plant APs, SWPs, and analogous animal signals, underscoring the complexity of measurement [121, 122]. Moreover, standard physiological measures of water stress and hydraulics remain better established for many field systems [123]. A lack of standardized protocols for electrode placement, amplification, filtering, and data reporting, along with the absence of open-access repositories, limits reproducibility and meta-analyses. Community consensus on concepts like a "plant electrophysiological phenotype" is still emerging [124].
- The concept of the "electrome" provides a holistic framework for interpreting plant electrical activity. Unlike single-event analyses of APs or VPs, the electrome considers the continuous, noisy electrical dynamics of the plant as a system-level indicator of physiological state. Statistical analysis of the electrome including amplitude distributions, frequency spectra, and spatiotemporal correlations can reveal subtle stress responses, memory effects, or systemic adaptation patterns that single-event measurements may miss.
- Future progress depends on integrating electrophysiological readouts with molecular and phenotypic layers. For example, chemical and hydraulic signalling under drought are well-characterized at molecular levels [125]. Coupling electrome analysis with transcriptomics, proteomics, and high-throughput phenomics could map electrical dynamics onto downstream adaptation pathways, enhancing mechanistic understanding and predictive modelling.
- The frontier is moving toward electroceuticals: modulating plant physiology via controlled electrical stimulation and biohybrid systems integrating living plants with electronic interfaces. While direct trials remain limited, technological pathways including wearable plant sensors, IoT networks, and edge/cloud analytics are emerging [33]. On a larger scale, distributed bioelectronic ecosystems could link plant networks to IoT and AI, allowing continuous monitoring of plant and landscape-level electrome patterns to inform sustainable management decisions.

7 Conclusion

Electrobiological signatures provide a rapid and sensitive way to detect how plants respond to environmental stress. By translating physiological changes into measurable electrical signals, plants can act as living sensors, revealing drought, heat, salinity, or pathogen stress before visible symptoms appear. This review highlights how electrical signals reflect underlying physiological processes and offer a non-destructive approach to monitoring plant health in real time. Advances in flexible electrodes, wireless monitoring, and data analysis now allow these signals to be tracked continuously, linking plant responses with management decisions in agriculture and environmental monitoring. Such approaches could support earlier stress detection and more efficient management of water, nutrients, and pests in cropping systems. Beyond agriculture, electrical signalling may also provide insights into plant–plant interactions, community responses, and ecosystem feedbacks under changing environmental conditions. These signals therefore offer a promising tool for studying plant responses at both individual and ecosystem levels. Future work should focus on improving signal reliability, developing standardized measurement protocols, and combining electrophysiological approaches with molecular and ecological data. Integrating these signals with emerging sensor technologies and data-driven models may further strengthen their use in predicting plant responses to environmental stress.

Data Availability Statement

Not applicable.

Funding

This work was supported without any funding.

Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

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Ethical Approval and Consent to Participate

Not applicable.

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