



Smart Biosensor Technologies for Real-time Detection of Plant Hormones: Integration of Nanomaterial-Enhanced Transduction Platforms, Wearable Sensing Architectures, and Wireless Data Transmission for Precision Plant Physiology and Agricultural Phenotyping

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Abstract

Plant hormones orchestrate critical physiological processes including growth, development, stress responses, and environmental adaptation, yet conventional analytical methods require destructive sampling and laboratory-based instrumentation that preclude real-time monitoring of dynamic hormonal fluctuations in living plants. Smart biosensor technologies have emerged as transformative tools enabling continuous, in situ detection of phytohormones through integration of biorecognition elements, nanomaterial-enhanced transduction mechanisms, and miniaturized electronic systems. This review examines advanced biosensing platforms for real-time plant hormone monitoring, emphasizing electrochemical, optical, and piezoelectric transduction strategies coupled with enzymes, aptamers, antibodies, and molecularly imprinted polymers as recognition elements. Nanomaterials including graphene, carbon nanotubes, quantum dots, and metallic nanoparticles enhance sensitivity, selectivity, and response kinetics while enabling miniaturization for wearable and implantable configurations. System integration encompasses signal processing circuits, wireless communication modules, and machine learning algorithms for automated data analytics. Applications span stress physiology, disease diagnostics, growth optimization, and precision agriculture, providing unprecedented temporal resolution of hormonal dynamics under field conditions. Critical challenges include improving long-term stability, achieving multiplexed detection in complex plant matrices, and scaling deployment across diverse crop systems. Future integration with Internet of Things infrastructures and artificial intelligence platforms promises data-driven decision support for next-generation precision agriculture and plant phenotyping.

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1. Introduction

Plant hormones, or phytohormones, function as endogenous signaling molecules regulating fundamental physiological processes including cell division, elongation, differentiation, reproductive development, senescence, and responses to biotic and abiotic stresses ^[1, 2]. Major hormone classes comprise auxins, cytokinins, gibberellins, abscisic acid, ethylene, brassinosteroids, jasmonates, salicylic acid, and strigolactones, each exhibiting distinct biosynthetic pathways, transport mechanisms, and concentration-dependent signaling cascades ^[3, 4]. The temporal and spatial dynamics of hormone accumulation dictate developmental programming and adaptive responses, with concentrations ranging from picomolar to micromolar levels

depending on tissue type, environmental conditions, and physiological status^[5,6]. Traditional analytical techniques for plant hormone quantification rely predominantly on mass spectrometry, high-performance liquid chromatography, enzyme-linked immunosorbent assays, and gas chromatography-mass spectrometry^[7, 8]. While providing excellent sensitivity and specificity, these methodologies necessitate destructive tissue sampling, extensive sample preparation, costly instrumentation, and laboratory expertise, rendering them incompatible with continuous monitoring of living plants under natural growth conditions^[9]. The inherent lag between sampling and analysis precludes real-time observation of rapid hormonal fluctuations occurring during stress perception, circadian oscillations, or developmental transitions^[10].

Smart biosensor technologies address these limitations through integration of biorecognition elements with transduction platforms capable of converting molecular binding events into quantifiable electrical, optical, or mechanical signals^[11, 12]. Recent advances in nanomaterials, microfabrication, flexible electronics, and wireless communication enable development of miniaturized, wearable, and implantable devices for continuous in planta hormone monitoring with minimal tissue damage^[13, 14]. Such platforms provide unprecedented temporal resolution for tracking hormonal dynamics, facilitating mechanistic studies of plant physiology and enabling data-driven precision agriculture strategies^[15].

This review examines state-of-the-art smart biosensor technologies for real-time plant hormone detection, emphasizing recognition element selection, transduction mechanism design, nanomaterial integration, system miniaturization, and field deployment considerations. Applications in plant stress monitoring, growth optimization, and precision crop management are discussed alongside critical challenges and future directions for translational implementation.

2. Smart Biosensor Technologies for Plant Hormone Detection

2.1. Biorecognition Elements for Hormone-Selective Detection

Biorecognition elements provide molecular selectivity by binding target hormones with high affinity and specificity, generating measurable signals upon interaction^[16]. Enzyme-based biosensors exploit catalytic reactions where hormone-responsive enzymes generate electroactive or chromogenic products proportional to hormone concentration^[17]. For instance, auxin oxidase catalyzes indole-3-acetic acid oxidation, producing hydrogen peroxide detectable via electrochemical reduction or colorimetric assays^[18].

Antibody-based immunosensors leverage antigen-antibody recognition, with monoclonal or polyclonal antibodies immobilized on transducer surfaces to capture target hormones^[19]. Competitive or sandwich immunoassay formats enable sensitive detection, though antibody production requires animal immunization and purification processes^[20]. Aptamers—single-stranded oligonucleotides selected via systematic evolution of ligands by exponential enrichment—offer synthetic alternatives with comparable affinity, enhanced stability, and chemical synthesis scalability^[21, 22]. Aptasensors incorporating hormone-specific aptamers demonstrate reversible binding suitable for continuous monitoring applications.

Molecularly imprinted polymers serve as synthetic receptors created by polymerizing functional monomers around hormone templates, generating recognition cavities complementary in size, shape, and chemical functionality^[23]. Following template removal, these biomimetic materials selectively rebind target hormones with affinities approaching biological receptors while offering superior thermal and chemical stability^[24].

2.2. Transduction Mechanisms and Signal Generation

Electrochemical transduction converts molecular recognition events into electrical signals through amperometric, potentiometric, or impedimetric detection^[25]. Amperometric biosensors measure current resulting from redox reactions of target analytes or enzymatic products at defined potentials, offering high sensitivity and rapid response times^[26]. Potentiometric sensors monitor potential changes arising from ion-selective membranes or field-effect transistor configurations, while impedimetric sensors detect changes in electrical impedance upon hormone binding to recognition elements immobilized on electrode surfaces^[27].

Optical transduction exploits changes in absorbance, fluorescence, luminescence, or refractive index^[28]. Fluorescent biosensors incorporate hormone-responsive fluorophores or fluorescence resonance energy transfer pairs, enabling sensitive detection through intensity, lifetime, or polarization measurements^[29]. Surface plasmon resonance sensors monitor refractive index changes at metal-dielectric interfaces upon hormone binding, providing label-free real-time detection^[30].

Piezoelectric transduction utilizes quartz crystal microbalances or surface acoustic wave devices where hormone binding increases mass loading, shifting resonant frequency proportionally^[31]. These label-free sensors offer real-time monitoring but require careful control of environmental parameters affecting frequency stability^[32].

2.3. Nanomaterial Integration for Performance Enhancement

Nanomaterials enhance biosensor performance through increased surface area for biorecognition element immobilization, improved electron transfer kinetics, and unique optical or catalytic properties^[33, 34]. Graphene and carbon nanotubes provide exceptional electrical conductivity, large surface-to-volume ratios, and biocompatibility, serving as electrode materials or signal amplification platforms^[35]. Functionalization with carboxyl, amino, or hydroxyl groups facilitates covalent attachment of enzymes, antibodies, or aptamers while maintaining electrochemical activity^[36].

Metallic nanoparticles including gold, silver, and platinum exhibit surface plasmon resonance, catalytic activity, and bioconjugation capabilities^[37]. Gold nanoparticles functionalized with thiolated aptamers enable colorimetric hormone detection through aggregation-induced color changes or electrochemical sensing via enhanced electron transfer^[38]. Quantum dots offer size-tunable photoluminescence for multiplexed fluorescent detection of multiple hormones simultaneously^[39].

Metal-organic frameworks and mesoporous silica provide high-capacity matrices for enzyme encapsulation and controlled hormone preconcentration, improving detection limits^[40]. Conducting polymers such as polyaniline and polypyrrole facilitate biorecognition element immobilization while contributing redox activity for signal generation^[41].

Table 1: Major plant hormones and corresponding

| Hormone Class | Representative Molecules | Biorecognition Elements | Transduction Mechanisms | Detection Range |
|---------------|---------------------------|----------------------------------------------|--------------------------------|------------------|
| Auxins | Indole-3-acetic acid, NAA | Auxin oxidase, anti-IAA antibodies, aptamers | Amperometric, fluorescent | 0.1–100 μ M |
| Cytokinins | Zeatin, kinetin, 6-BA | Anti-cytokinin antibodies, MIPs | Electrochemical impedance, SPR | 1 nM–10 μ M |
| Abscisic acid | ABA | Anti-ABA antibodies, aptamers, ABA receptors | Potentiometric, fluorescent | 0.01–100 μ M |
| Gibberellins | GA3, GA4 | Anti-GA antibodies, MIPs | Amperometric, SPR | 0.1–50 μ M |
| Ethylene | Ethylene gas | Ethylene receptors, metal oxide sensors | Conductometric, optical | 0.01–100 ppm |
| Jasmonates | Jasmonic acid, JA-IIe | Anti-JA antibodies, enzymes | Electrochemical, fluorescent | 1 nM–10 μ M |

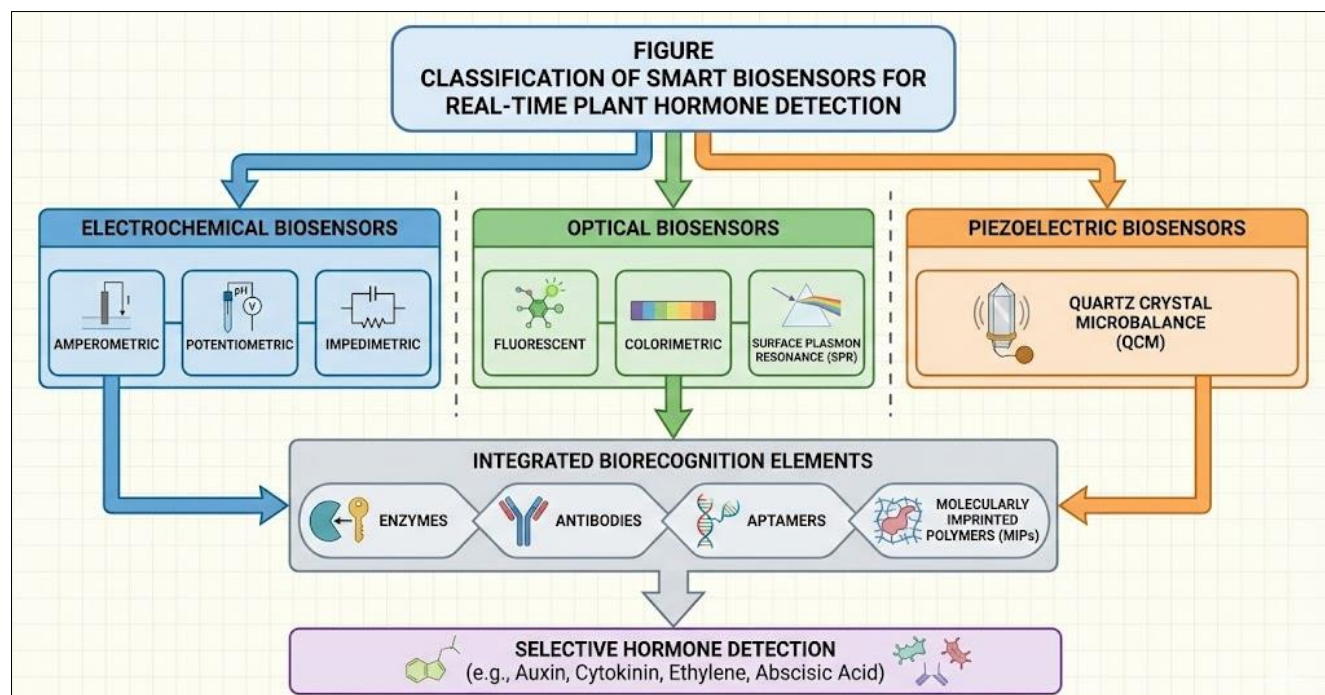


Fig 1: Classification of smart biosensors for real-time plant hormone detection based on transduction mechanisms. The schematic illustrates electrochemical biosensors (amperometric, potentiometric, impedimetric), optical biosensors (fluorescent, colorimetric, surface plasmon resonance), and piezoelectric biosensors (quartz crystal microbalance) integrated with various biorecognition elements including enzymes, antibodies, aptamers, and molecularly imprinted polymers for selective hormone detection.

3. Real-time Sensing and System Integration

3.1. Signal Processing and Sensitivity Enhancement

Real-time hormone monitoring requires signal processing circuits converting transducer outputs into digital data for wireless transmission and analysis [42]. For electrochemical sensors, potentiostat circuits maintain defined electrode potentials while measuring resulting currents with sub-nanoampere resolution through operational amplifier configurations and analog-to-digital converters [43]. Lock-in amplifiers enhance signal-to-noise ratios by synchronous detection at specific modulation frequencies, improving detection limits in field environments with electrical interference [44].

Differential pulse voltammetry and square wave voltammetry provide enhanced sensitivity compared to steady-state measurements by minimizing charging currents and background signals. For optical sensors, photodiode arrays coupled with transimpedance amplifiers and temperature-compensated reference channels enable ratiometric fluorescence measurements robust against illumination fluctuations.

Signal averaging, baseline correction algorithms, and Kalman filtering improve temporal resolution while reducing noise. Machine learning algorithms including artificial neural

networks and support vector machines enable multivariate calibration accounting for interferences, temperature effects, and sensor drift.

3.2. Wearable, Implantable, and Minimally Invasive Sensor Platforms

Wearable plant sensors employ flexible substrates and stretchable electronics conforming to plant surfaces for non-invasive continuous monitoring. Screen-printed electrodes on polyimide or polyethylene terephthalate films incorporate working, reference, and counter electrodes within millimeter-scale footprints, applicable to leaves, stems, or fruits. Microfluidic sampling systems collect xylem or phloem sap through microneedles or porous membranes, delivering fluids to sensing chambers with minimal tissue damage.

Implantable sensors utilize biocompatible materials including parylene, polyethylene glycol hydrogels, or silk fibroin for subcutaneous placement within stems or roots. These devices monitor apoplastic or symplastic hormone concentrations with reduced interference from surface contaminants. Minimally invasive designs employ microfabricated needle electrodes or fiber-optic probes inserted through small incisions, healing rapidly without compromising plant health.

Biodegradable sensors fabricated from cellulose, chitosan, or polylactic acid decompose naturally after deployment, eliminating retrieval requirements for large-scale field applications. Such transient electronics maintain functionality for days to weeks, sufficient for monitoring critical developmental windows or stress episodes.

3.3. Wireless Communication and Data Analytics

Wireless data transmission enables remote monitoring of distributed sensor networks across agricultural fields or controlled environment facilities. Bluetooth Low Energy protocols provide short-range communication with minimal power consumption, suitable for greenhouse applications. LoRaWAN and NB-IoT networks offer long-range connectivity for outdoor deployments, transmitting sensor data to cloud servers for centralized storage and analysis.

Energy harvesting strategies including photovoltaic cells, piezoelectric generators, or plant microbial fuel cells sustain sensor operation without battery replacement. Power management circuits regulate energy storage and consumption, enabling autonomous operation for months to years.

Cloud-based analytics platforms aggregate data from multiple sensors, applying statistical process control, anomaly detection, and predictive modeling. Integration with meteorological data, soil moisture sensors, and satellite imagery provides comprehensive environmental context for interpreting hormonal dynamics. Dashboards visualize temporal trends, spatial distributions, and correlations between hormone levels and growth metrics, facilitating data-driven decision-making.

Table 2: Smart biosensor platforms, recognition elements, and performance metrics for plant hormone monitoring

| Biosensor Platform | Recognition Element | Transduction | Target Hormone | LOD | Response Time |
|-------------------------|---------------------|----------------|----------------|--------|---------------|
| Graphene-based FET | Anti-IAA aptamer | Potentiometric | IAA | 10 nM | <5 min |
| AuNP-modified electrode | Auxin oxidase | Amperometric | IAA | 50 nM | 2 min |
| QCM immunosensor | Anti-ABA antibody | Piezoelectric | ABA | 1 nM | 10 min |
| Fluorescent aptasensor | Cytokinin aptamer | Optical | Zeatin | 5 nM | 3 min |
| MIP-based sensor | Imprinted GA3 | Impedimetric | GA3 | 100 nM | 8 min |
| Fiber optic sensor | Ethylene receptor | Optical | Ethylene | 10 ppb | 1 min |

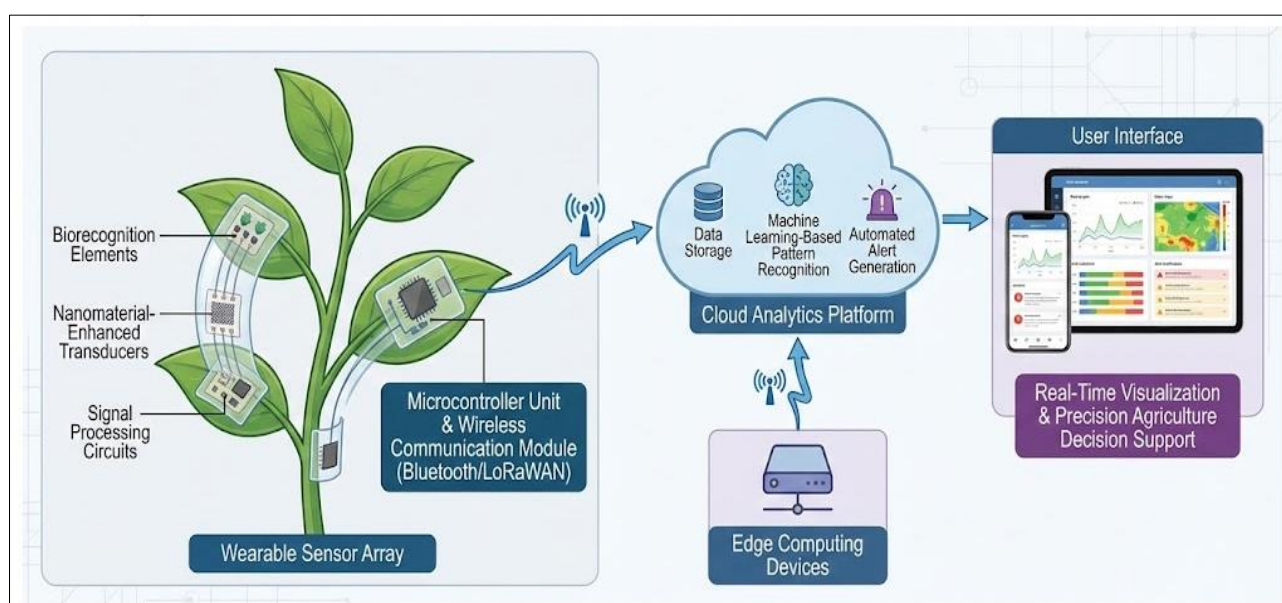


Fig 2: Schematic representation of an integrated smart biosensor system for in planta hormone monitoring and wireless data transmission.

The diagram depicts a wearable sensor array positioned on plant leaves or stems, incorporating biorecognition elements, nanomaterial-enhanced transducers, signal processing circuits, microcontroller units, and wireless communication modules (Bluetooth/LoRaWAN). Data flows from sensors through edge computing devices to cloud analytics platforms, enabling real-time visualization, machine learning-based pattern recognition, and automated alert generation for precision agriculture decision support.

4. Applications in Plant Science and Precision Agriculture

4.1. Stress and Disease Monitoring

Real-time hormone monitoring enables early detection of stress responses before visible symptoms manifest. Abscisic acid accumulation signals water deficit, osmotic stress, or salinity exposure, allowing precision irrigation adjustments. Ethylene biosynthesis increases during pathogen infection, mechanical damage, or senescence, providing diagnostic markers for disease management]. Salicylic acid and jasmonic acid profiles differentiate between biotrophic and necrotrophic pathogen attacks, guiding targeted pesticide applications.

Continuous monitoring during abiotic stress episodes reveals temporal dynamics of hormone signaling cascades, identifying critical intervention windows for protective treatments. Multiplexed biosensors detecting multiple hormones simultaneously elucidate crosstalk networks coordinating stress adaptation.

4.2. Growth Regulation and Phenotyping

Auxin and cytokinin ratios regulate shoot-root development, cell expansion, and lateral organ formation. Real-time tracking of these hormones during vegetative growth enables optimization of photoperiod, nutrient supply, and growth

regulator applications for desired plant architectures. Gibberellin monitoring during reproductive transitions identifies optimal timing for flowering induction or harvest. High-throughput phenotyping platforms integrating biosensor arrays with imaging systems correlate hormonal profiles with morphometric traits, enabling genome-wide association studies and selection of elite genotypes. Wearable sensors deployed on multiple plants simultaneously generate population-level data for breeding programs targeting stress tolerance or yield improvement.

4.3. Precision Irrigation and Nutrient Management

Soil moisture sensors coupled with plant hormone biosensors

provide feedback for irrigation scheduling based on plant water status rather than soil metrics alone. Abscisic acid levels reflect stomatal closure and drought stress perception, signaling irrigation needs before wilting occurs. Ethylene accumulation in waterlogged soils indicates hypoxia, triggering drainage interventions.

Nutrient deficiencies alter hormone homeostasis, with cytokinins declining under nitrogen limitation and auxins responding to phosphorus availability. Integrated sensor networks combining hormone detection with nutrient-sensitive electrodes enable site-specific fertilization, reducing environmental impacts while maintaining productivity.

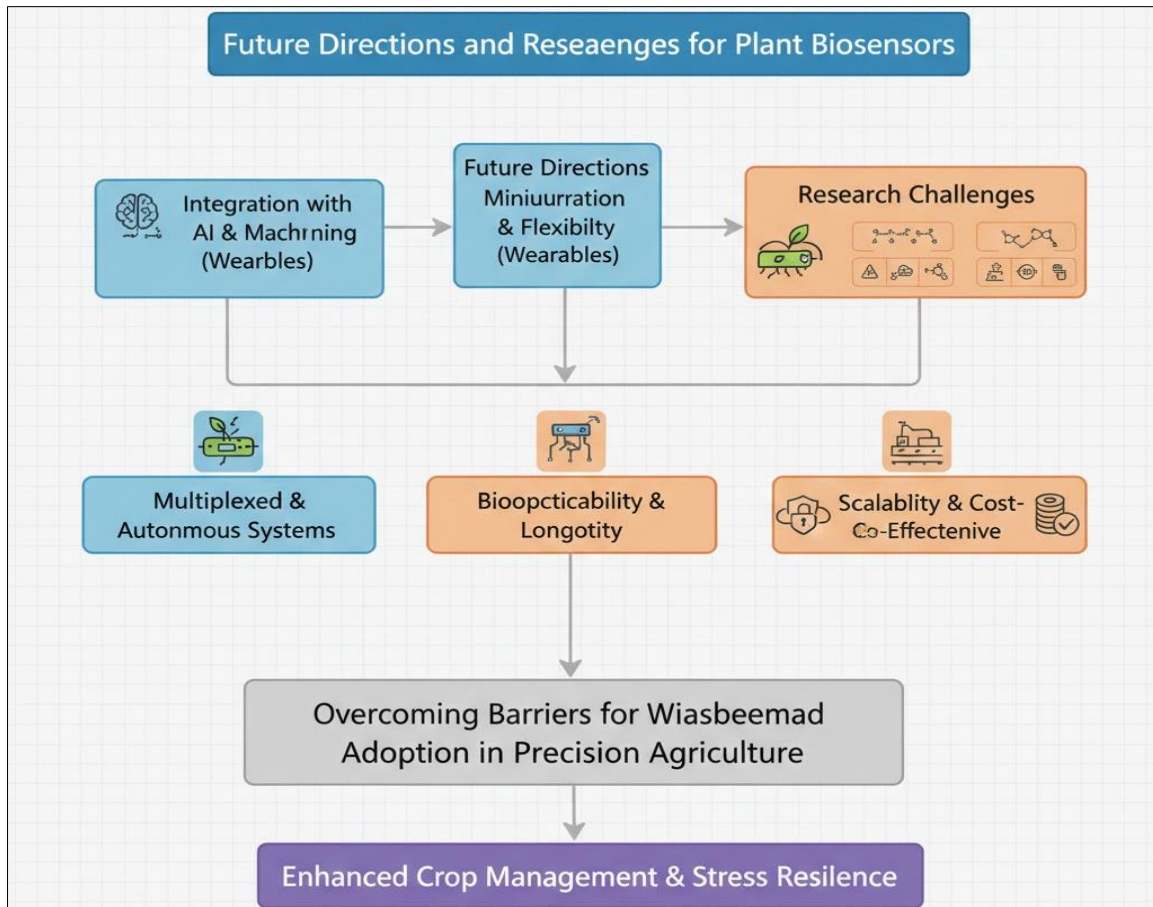


Fig 3: Application of wearable and minimally invasive biosensors for continuous monitoring of plant hormonal dynamics under field conditions. The illustration shows sensors deployed on various crop species in agricultural settings, with representative time-series data demonstrating hormone fluctuations in response to irrigation events, pathogen infection, and diurnal cycles. Wireless data transmission to mobile devices and cloud platforms enables remote monitoring and automated decision support for precision agriculture management.

5. Challenges and Future Perspectives

5.1. Selectivity, Stability, and Long-term Operation

Achieving selectivity in complex plant matrices containing structurally similar phytohormones, metabolites, phenolics, and interfering compounds remains challenging. Fouling of sensor surfaces by proteins, polysaccharides, or particulates degrades performance over time. Strategies including antifouling coatings, self-cleaning electrodes, and reference compensation algorithms improve stability.

Long-term operation requires biorecognition elements retaining activity under field conditions with fluctuating temperature, humidity, and pH. Enzyme stabilization through crosslinking, encapsulation, or genetic engineering extends operational lifetimes. Regenerable sensors employing reversible binding mechanisms enable reuse without

replacement.

Calibration drift necessitates periodic recalibration or self-calibration protocols comparing sensor outputs to internal standards. Automated microfluidic calibration systems delivering known hormone concentrations improve measurement accuracy.

5.2. Field Deployment and Scalability

Transitioning from laboratory prototypes to field-deployable devices requires ruggedization against environmental extremes, mechanical stress, and biological degradation. Packaging materials must balance protection with permeability for analyte access. Manufacturing scalability through roll-to-roll printing, injection molding, or automated assembly reduces costs for agricultural implementation.

Power requirements for continuous wireless operation challenge energy budgets, particularly for remote deployments. Ultra-low-power electronics, duty-cycled operation, and efficient energy harvesting extend deployment durations. Solar-powered nodes enable multi-season monitoring campaigns.

Standardization of sensor protocols, data formats, and communication interfaces facilitates interoperability across platforms and integration with existing farm management systems. Regulatory considerations for sensor deployment in food crops require biocompatibility validation and risk assessments.

5.3. Integration with AI and Digital Agriculture Platforms

Machine learning models trained on multimodal sensor data

predict crop responses, optimize interventions, and automate decision-making. Deep learning architectures process time-series hormone data alongside environmental variables, identifying complex patterns undetectable through conventional analysis. Federated learning enables privacy-preserving model training across multiple farms without centralizing sensitive data.

Digital twin frameworks simulate plant hormone dynamics based on real-time sensor inputs, forecasting responses to management scenarios. Reinforcement learning algorithms optimize irrigation, fertilization, and climate control strategies through continuous interaction with sensor feedback. Blockchain-based data provenance ensures traceability and authenticity for precision agriculture applications.

Table 3: Advantages, limitations, and deployment challenges of smart biosensors in real-time plant hormone analysis

| Aspect | Advantages | Limitations | Deployment Challenges |
|--------------------------|-------------------------------------------------------------|--------------------------------------------|----------------------------------------------------|
| Electrochemical sensors | High sensitivity, miniaturization, low cost, rapid response | Fouling, interference, reference stability | Field calibration, electrode passivation |
| Optical sensors | Label-free detection, non-invasive, multiplexing capability | Light interference, photobleaching, size | Power for illumination, optical alignment |
| Wearable platforms | Continuous monitoring, minimal damage, real-time data | Mechanical stress, biocompatibility | Attachment reliability, plant growth accommodation |
| Wireless systems | Remote access, scalability, data integration | Power consumption, communication range | Network coverage, data security |
| Nanomaterial integration | Enhanced sensitivity, selectivity, surface area | Toxicity concerns, aggregation, cost | Reproducible synthesis, long-term stability |

6. Conclusion

Smart biosensor technologies represent a paradigm shift in plant hormone analysis, enabling continuous real-time monitoring under natural growth conditions that was previously unattainable through conventional analytical techniques. Integration of selective biorecognition elements with nanomaterial-enhanced transduction platforms, miniaturized electronics, and wireless communication systems provides unprecedented insights into dynamic hormonal regulation of plant physiology. Applications spanning stress diagnostics, growth optimization, and precision agriculture demonstrate translational potential for improving crop productivity, resource efficiency, and environmental sustainability.

Critical advances in sensor selectivity, long-term stability, and field deployability are essential for widespread adoption. Emerging strategies including biomimetic receptors, self-calibrating systems, and biodegradable materials address current limitations. Integration with artificial intelligence, Internet of Things infrastructures, and digital agriculture platforms promises data-driven decision support systems leveraging real-time hormonal information alongside environmental and phenotypic data. Future research should prioritize multiplexed detection platforms, cross-species sensor validation, and economic assessments demonstrating return on investment for commercial agriculture. As these technologies mature, smart biosensors will become integral components of next-generation precision agriculture, enabling sustainable intensification through molecular-level monitoring and control of crop performance.

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