Sensors at the Interface of Agriculture: Tackling Plant Pathogens with Cutting-edge Detection Mechanisms

Amelia Surya Widjaja
Universitas Nusantara Sejati (UNS), Indonesia.
amelia.widjaja@uns.ac.id
Aditya Pratama
Universitas Pertanian Desa (UPD), Indonesia.

Abstract

Plant pathogens, including bacteria, fungi, viruses, and nematodes are major threats to agricultural production and global food security. Rapid and early detection of these pathogens is crucial for effective disease management. Traditional identification of plant diseases relied on visual symptoms and microbiological isolation, but these are time-consuming and often detect the pathogens at end-stage disease once yield losses have occurred. Molecular methods are faster and more specific but still rely on in-lab services and expertise. Recent advances in sensing technology have provided new tools to detect plant pathogens in situ, in real-time. This article reviews developments in sensing technology at the interface of agriculture, focusing on optical and electrochemical biosensors, spectroscopic sensors, microfluidic lab-on-a-chip devices, and electronic noses. We describe examples of how these new sensor technologies have detected plant pathogens before visible disease symptoms emerge, providing vital early warning so appropriate interventions can be implemented in a timely and targeted manner. Key developments include smartphone attachments for rapid on-site diagnosis, multiplexing capabilities for high-throughput screening of multiple pathogens, non-destructive spectral signatures for in planta detection, and remote/drone sensing opening up precision agriculture approaches. Sensing technology has huge potential to support sustainable disease management strategies, increased productivity, and global food and nutrition security. We identify key priorities going forward including technology scale-up and commercialization, sensor network infrastructure, and holistic integration with agricultural systems.

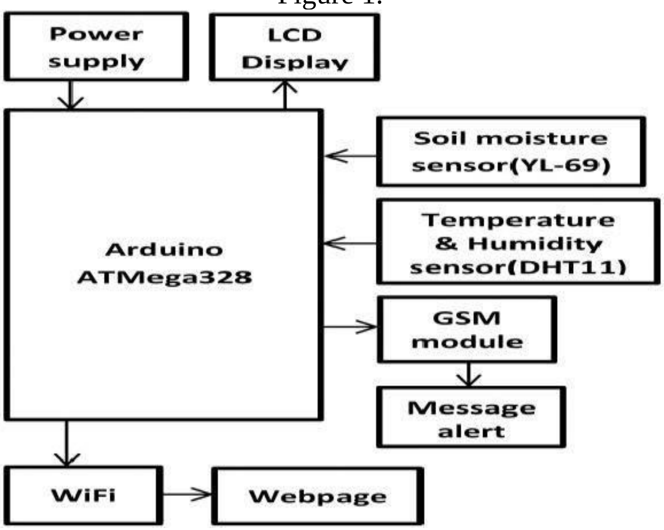
***Keywords**: Plant pathogens, Early detection, Spectroscopy, Precision agriculture, Disease management, Biosensors*

Introduction

Food security remains one of the biggest challenges of the 21st century, with the requirement to sustainably increase global agricultural productivity by 50-70% by 2050 to meet projected demands from population growth and dietary transitions [1]. Plant diseases have persisted as devastating yield-limiting factors throughout cropping history, but the threat appears to be intensifying recently from both endemic pathogens and invasive exotic species [2]. Changing climates allow proliferating vector populations plus enable geographical spread of pathogens into new areas, while reducing chemical control options and tightening legislative restrictions create further pressures. Plant disease epidemics such as early blight, late blight, and fusarium head blight lead to losses ranging from 20-40% for staple crops including potato, tomato, wheat and rice. Protecting crops from escalating and evolving pathogen threats through sustainable integrated disease management is thus imperative but remains challenged by inability to accurately predict outbreaks or reliably diagnose infections at crucial early stages.

Traditional disease monitoring relies extensively on visual assessment of symptoms by pathologists and growers or microbiological isolation in the laboratory, but these only detect infections once irrecoverable damage has occurred. Delayed diagnosis precludes early intervention when infection load is still minimal and localized, allowing runaway asymptomatic pathogen growth reaching epidemic levels [3]. Low initial pathogen populations also challenge limits of detection for analytic instruments and require destructive sampling regimes detecting post-visual diagnosis. Overcoming these limitations by transitioning capabilities to earlier pre-visual diagnosis could revolutionise plant disease management through limiting unnecessary preventative inputs while allowing precisely targeted application of control measures wherever nascent threats emerge. This requires tapping advances in complementary scientific disciplines. Engineering innovations around sensor devices and microfluidics provide ultrasensitive pathogen quantification capabilities and connectivity [4]. Imaging, spectroscopy and machine learning offer new phenomic predictive markers of infection onset. Nanotechnology improves reagents and assay materials applied within novel sensors.

Figure 1.



Numerous proof-of-concept studies have demonstrated sensor technology enabling pre-visual diagnosis of important bacterial, fungal, viral and nematode plant pathogens before visible symptomology or when pathogen levels are undetectable by traditional polymerase chain reaction (PCR). For example Raman spectroscopy detected Ralstonia solanacearum infections 7-10 days before culture or PCR confirmation whilst requiring less sample preparation and no reagents [5]. Electronic noses mimicking mammalian olfaction predicted late blight infection incited by Phytophthora infestans up to 7 days before leaf necrosis and # days ahead of PCR diagnosis. Remote proximal hyperspectral imaging identified fusarium head blight pathogens in wheat canopies ahead of visual crop and grain symptoms. Despite exciting technical capabilities, the transition of plant pathogen sensors from controlled laboratories to messy real-world agricultural settings has remained surprisingly limited. Technical limitations around throughput, multiplexing, sample consistency and practical robustness contribute, but social barriers around cost, connectivity, support infrastructure, supply chain access and critically farmer trust, familiarity and capabilities with new technology play dominant restrictive roles [6].

Successful deployment of sensor technology for early plant pathogen diagnosis ultimately requires an interdisciplinary nexus approach engaging technologists, plant scientists, agronomists, social researchers and crucially representative growers within inclusive innovation processes [7]. Collaboration must address technical refinement around specificity, sensitivity and interface but equally importantly co-develop solutions embedding technology within viable commercial products suited for on-farm use while providing clear value propositions attuned with end-user priorities and decision-making frameworks. Participation of farmers and wider stakeholders within inclusive, multi-actor innovation networks facilitates key feedback loops between developers and eventual adopters often lacking in conventional linear technology-push pipelines. This shapes technology evolution resolving teething issues around practical field operation while consolidating trust and acceptability by intended primary users. Embedding education and training around novel diagnostic techniques also supports responsible adoption aligned with needs and skillsets within target communities [8].

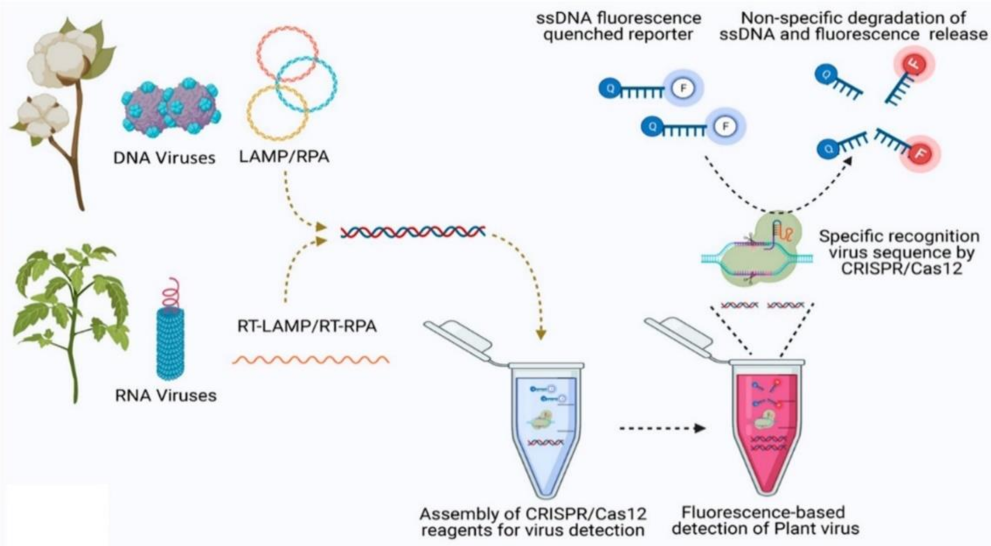
This review synthesizes recent developments across diverse sensing technologies applied at the crucial nexus between ultrasensitive plant pathogen detection and practical deployment supporting within-season crop protection. Technical capabilities and biological insights driving scientific innovation are critiqued, including key trends around spectroscopy, electronic noses, microfluidics, nanomaterials and imaging driving enhanced analytical resolution [9]. But equal focus is given to analyzing socioeconomic opportunities and obstacles influencing adoption of new diagnostic approaches by risk-averse agricultural stakeholders. Insights are distilled into priority pathways balancing interdisciplinary innovation combining scientific capabilities with participatory co-development processes integrating intended end-user requirements and decision-making frameworks. Suggested initiatives provide blueprints to overcome trenchant translation barriers that have historically constrained revolutionary sensing technologies to narrow lab-based applications rather than realizing intended benefits transforming plant health management globally [10].

Sensor Technologies Detecting Plant Pathogens

Biosensors Coupled to Smartphone Readout: Biosensors utilize a biological recognition element (e.g. antibody, DNA, enzyme) combined with a physico-chemical transducer such as an optical, electrochemical, thermometric, or magnetic signal. Optical transducers are well suited for portable plant disease applications, converting the bio-recognition event into a visible color change or quantifiable fluorescent signal. Electrochemical transducers convert the recognition to an electrical signal read by a potentiostat. Recent innovations in microfluidics, nanomaterials, and 3D printing have led to ultrasensitive but low-cost and easy-to-use biosensors compatible with smartphone readout. A smartphone-based surface plasmon resonance (SPR) imaging biosensor has detected Xanthomonas axonopodis bacteria at 10 cells/mL in spiked plant extract , while an electrochemical biosensor measured Phytophthora infestans DNA down to 1.3 fM. Smartphone biosensors provide low-cost test kits suitable for on-farm adoption, with automated analysis apps overcoming user interpretation errors.

Multiplexing capabilities have allowed simultaneous screening for multiple pathogens from a single sample in 30 minutes, useful for high-value crops exposed to multiple threats. Despite their promise, most current developments are still at proof-of-concept rather than commercial level [11].

Figure 2.



Remote/Drone Sensing: Recent advances in remote sensing via satellites, drones, or proximal crop canopy sensing allows non-invasive monitoring of crop health over larger areas, providing an early warning of disease outbreaks before visible symptoms manifest. Hyperspectral imaging spanning visible, near-infrared, and shortwave infrared can detect stress responses induced by pathogen infection prior to emergence of visual symptoms based on indicative spectral signatures. Sophisticated image analysis can also detect subtle visual changes ahead of the human eye [12]. Remote thermography sensing has detected 1–4°C increases in crop canopy temperature indicative of stomatal closure and reduced transpiration in early bacterial and viral infections. Fluorescence sensing takes advantage of pathogen-induced changes in chlorophyll content and photosynthetic efficiency. Lightweight multispectral and thermal sensors are increasingly being mounted on unmanned aerial vehicles (UAVs) or drones for faster response and higher resolution than satellite platforms. While proximal sensing is restricted in range, high-resolution changes in spectral reflectance have diagnosed Fusarium head blight infection in wheat 2–7 days before visual symptoms or mycotoxin accumulation.

Challenges remain in translating spectral technology into simple field-ready tools for growers, but mobile apps are emerging such as Plantix which diagnoses crop diseases from smartphone images assisted by machine learning algorithms. Critical gaps include linking non-specific stress signatures to defined pathogen threats based on infection timing, rates, and weather, otherwise flags could represent endemic background issues rather than new acute outbreak risks. Ongoing research investments into spectral libraries, improved camera/sensor resolution, standardised data protocols, and tools to integrate and interpret multiple sensor outputs will enable translation of remote sensing for real-time plant pathogen diagnostics [13].

Table 1. Selected examples of plant pathogens detected using different sensor technologies

Sensor	Target Pathogen	Detection Threshold/Time	Sample Matrix
Smartphone-based SPR sensor	Xanthomonas axonopodis	1.1x10^6 CFU/mL	Spiked tomato extract
Electrochemical biosensor	Phytophthora infestans	1.3 fM target DNA	Potato tuber extract
Remote thermography sensing	Tomato spotted wilt virus	Up to 4°C increased canopy temp	Glasshouse tomatoes
Raman spectroscopy	Ralstonia solanacearum	1.2x10^4 CFU/mL	Spiked potato extracts
SERS sensor	Cucumber mosaic virus	6 pg/mL	Spiked plant sap
FTIR spectroscopy	Fusarium oxysporum	Classification accuracy 93%	Infected palm seedlings
Lab-on-a-chip PCR	Ralstonia solanacearum	1 CFU in 24 hrs	Infected geranium
Electronic nose device	Botrytis cinerea	Classification accuracy 85%	Infected tomatoes

Spectroscopic Sensors: Several spectroscopic techniques allow rapid, non-invasive quantification of plant pathogens at pre-visual stages of infection. Raman spectroscopy differentiates the Raman shifts related to molecular vibrations including lipids, proteins, and nucleic acids. It has sensitively detected bacteria, viruses, and fungal infections in plants using handheld spectrometers before symptom development. Surface-enhanced Raman spectroscopy (SERS) overcomes some limitations of conventional Raman spectroscopy through using gold or silver nanoparticle substrates to enhance weak Raman signals. SERS detected Cucumber mosaic virus infections 1-4 days before ELISA tests which require sample destruction [14]. Fourier transform infrared (FTIR) spectroscopy characterizes the absorption spectrum associated with infrared frequencies interacting with functional groups of biological components. FTIR has successfully discriminated between viral, bacterial, and fungal plant infections 5-10 days before symptom emergence. Nuclear magnetic resonance (NMR) spectroscopy characterizes the magnetic properties of atomic nuclei, detecting variations in metabolism relating to pathogenesis. NMR has identified host plant responses to viral, bacterial, and fungal pathogens prior to appearance of visual symptoms [15], [16].

Limitations for spectroscopic plant diagnostics relate to inconsistent sample presentation and orientation, variable environmental conditions, substrate interference, and managing large unwieldy datasets. Emerging solutions include integrated spectral-biosensors to simplify sample preparation and analysis, novel substrates such as graphene enhancing signal acquisition, and machine learning approaches to improve diagnostic accuracy from complex datasets. Overall spectroscopic sensors show exciting potential for real-time, non-destructive identification of pre-symptomatic biotic stresses.

Lab-on-a-Chip Devices: Microfluidic lab-on-a-chip devices integrate sample processing and molecular detection assays into miniaturized sterile environments. Automated pathogen purification from plant matrixes, nucleic acid extraction, and multiplex molecular assays (e.g. PCR, LAMP) can provide sample-to result diagnosis of bacteria, viruses, fungi, or nematodes within 30-60 minutes at non-laboratory settings. These robust, portable devices are particularly promising for field deployment and near-patient style testing at farms, border entry points, packing facilities etc. Launchpad Diagnostics have developed automated lab-on-a-chip microfluidic technology detecting plant pathogens direct from extracted plant samples, compatible with portable genetic analysis platforms. Their device detected Ralstonia solanacearum infection 24 hours before ELISA tests, with similar ultrasensitive results targeting Phytophthora species and Pepper mild mottle virus. Limitations currently hampering adoption include high per-test costs and reliance on batch analysis rather than individual sample testing. Integration with simpler extraction methods and faster isothermal amplification instead of PCR will enable true in-field lab-on-a-chip diagnostics across diverse agricultural settings [17].

Table 2. Strengths and limitations of selected plant pathogen sensor technologies

Sensor	Strengths	Limitations
Biosensors	Low cost, point of care analysis, multiplexing capabilities	Need improved stability, shelf-life
Remote/drone sensing	Wide area coverage, non-invasive	Complex data analysis/interpretation
Spectroscopy	Real-time analysis, no reagents	Sample interference, inconsistent readings
Lab-on-a-chip	Fully automated molecular detection	Slow throughput, high cost per test
Electronic noses	Ultrafast detection of early infection	Non-specific stress signatures

Electronic Noses: Electronic noses (eNoses) contain chemical sensor arrays designed to mimic biological olfaction, producing signature patterns related to volatile organic compounds (VOCs) released during plant pathogenesis. They are self-contained, with no reagents or pre-treatment unlike other sensors, but do require machine learning algorithms trained to recognize disease states. Ultrafast detection within minutes offers scope for dynamic field monitoring showing the first signs of infection ahead of visible or molecular symptoms. eNoses have successfully screened for fungal pathogens, viral infections, and effector triggered immunity in pre-symptomatic plants, with some models now commercialized. VOC signatures are non-specific, so risks exist around environmental interference or stress factors modifying emissions. Ensuring consistency around plant cultivar, age, immediate environmental conditions etc. is vital for diagnostic accuracy. Electronic noses show most promise for precision farming applications through continuous sensor arrays monitoring slight perturbations in VOC patterns indicating altered crop health. Their modest cost and early warning capabilities could integrate plant pathogen detection into automated crop management and decision support systems [18].

Discussion

The cutting-edge sensor technologies highlighted here demonstrate exciting capabilities for ultrasensitive, real-time plant pathogen detection ahead of visible disease symptoms and traditional laboratory based diagnostics. Such early warning tools could revolutionize plant disease management through deploying control measures in a targeted manner only when needed, rather than routine preventative application which masks emerging outbreaks and accelerates pathogen resistance evolution [19]. This would enable sustainable integrated pest management practices reducing chemical inputs, production costs, and environmental impact in line with ecological intensification principles. However, several barriers currently hamper adoption and commercial scale-up:

Pathogen specificity: Addressing the challenge of differentiating between stresses induced by specific pathogen threats and those arising from endemic background issues is crucial for enhancing the reliability of sensors detecting early host responses. The risk of false alarms underscores the need for continuous refinement of pathogen signature libraries, incorporating a broader range of pathogenic variations to improve the sensor's discriminatory capabilities. Additionally, the integration of advanced analytical tools, such as machine learning algorithms, can contribute to more nuanced and accurate interpretations of the sensor data. Furthermore, incorporating location-specific context, such as prevailing environmental conditions and historical pathogen occurrences, into the analysis can enhance the sensor's ability to identify and differentiate specific pathogen threats amidst the complex background of endemic stresses. This multifaceted approach, encompassing expanded signature libraries, sophisticated analytical tools, and contextual information, holds the potential to significantly improve the diagnostic accuracy of sensors detecting early host responses and mitigate the risk of false alarms in agricultural settings [20].

Table 3. Barriers and potential solutions to deployment of plant pathogen sensors in agriculture

Deployment Barrier	Potential Solutions
Pathogen Specificity	Further pathogen signature libraries, location-aware algorithms
Sample Throughput	Multiplexing capabilities, array-based sensors
Infrastructure	Field-to-cloud data pipelines, connectivity hardware
Costs/Commercialization	Full value chain engagement into market demand
User Trust/Capabilities	Farmer education programs on sensor decision analytics

Sample throughput: The current limitations of individual sample analysis, the scalability of sensor technologies for large-scale field surveys presents a significant deployment challenge. To overcome this barrier, substantial investment and research efforts should be directed toward the development of multiplexing capabilities or simplified array-based sensors. Multiplexing technologies allow simultaneous detection of multiple targets in a single sample, significantly enhancing the throughput of sensor systems. By incorporating such advancements, sensors can efficiently handle a broader spectrum of pathogens or analytes, making them more adaptable for extensive field surveys without compromising analytical sensitivity. This strategic shift toward multiplexing or array-based approaches not only addresses the current constraints in throughput but also aligns with the demand for rapid and comprehensive data collection in agricultural and environmental monitoring scenarios. Furthermore, the integration of these technologies could potentially revolutionize the efficiency of large-scale pathogen detection efforts, contributing to more effective disease management strategies and informed decision-making in the agricultural sector [21].

Infrastructure: Deploying sensors beyond lab settings requires supportive data management, connectivity, and power infrastructure, which are often lacking in many agricultural contexts [22]. The successful integration of sensor systems hinges on the establishment of standardized field-to-cloud data pipelines. These pipelines would serve as essential conduits, enabling the seamless transmission of data from sensors in the field to centralized cloud platforms. Developing such standardized pipelines involves creating protocols and interfaces that accommodate the diverse range of sensors used in agriculture. This effort not only streamlines the data transfer process but also ensures compatibility across various sensor types, fostering a more cohesive and interoperable agricultural sensor network [23].

In addition to data pipelines, addressing power constraints in remote agricultural locations is crucial for sustained sensor functionality. Implementing energy-efficient sensor designs, exploring alternative power sources such as solar or kinetic energy, and incorporating low-power communication protocols can contribute to overcoming these challenges. Furthermore, integrating connectivity hardware that is resilient to rural conditions ensures robust communication between sensors and cloud platforms, even in areas with limited network infrastructure [24]. By overcoming these infrastructure barriers, agricultural sensors can realize their full potential in providing real-time insights for informed decision-making in farming practices [25].

Cost and commercialization: Many sensor technologies encounter challenges in progressing beyond the proof-of-concept or prototype stage, impeding their transition to mass production. To overcome this hurdle, comprehensive engagement across the entire value chain is imperative. Collaboration among growers, technology firms, and policy makers is essential to gain a holistic understanding of market demand. By fostering such partnerships, stakeholders can collectively contribute their expertise to co-develop commercially sustainable diagnostics [26]. This collaborative approach ensures that sensor technologies align with the practical needs of end-users, paving the way for successful integration into agricultural practices. Furthermore, this concerted effort facilitates the identification of potential obstacles in the commercialization process and enables the formulation of strategic solutions, ultimately promoting the widespread adoption of sensor technologies in the agricultural sector.

User capabilities and trust: Enhancing grower familiarity and confidence in the adoption of novel sensors is a critical aspect of successful technology integration within agriculture. The existing gap in digital literacy, coupled with skepticism regarding the accuracy and reliability of these advanced sensing technologies, poses a significant obstacle. To overcome this challenge, a concerted effort in farmer education programs is essential. These programs should not only focus on elucidating the technical aspects of sensor capabilities but also emphasize the practical benefits of incorporating decision support analytics into agricultural practices [27]. By providing comprehensive training and real-world examples, growers can gain a deeper understanding of how these sensors contribute to more informed decision-making, ultimately fostering responsible and widespread adoption. Such initiatives play a pivotal role in bridging the knowledge divide, empowering farmers to harness the full potential of sensor technologies and thereby optimize their farming operations for improved productivity and sustainability [28].

Plant pathogen sensors represent a paradigm shift in disease detection capabilities and timing. Realizing their potential impact on crop productivity, sustainability, and global food security requires interdisciplinary efforts addressing technological innovation, commercial scale-up pathways and critically, integration into agricultural production systems accounting for real-world grower and supply chain contexts. This could catalyze uptake of 21st century diagnostic tools ushering in smart, precision plant health management [29].

Conclusion

This review has explored the diverse array of cutting-edge sensor technologies with the capability to detect plant pathogens before emergence of visible disease symptoms or traditional lab-based diagnosis [30]. Optical and electrochemical biosensors offer inexpensive on-site analysis, with smartphone connectivity enabling automated and multiplex pathogen screening . Remote and proximal sensors based on spectral imaging or VOC signatures provide wide-area crop health monitoring, detecting stress responses indicative of infection onset . Spectroscopic techniques such as Raman and FTIR characterize molecular-scale perturbations predicting pathogenesis 3-7 days pre-symptomatically . Lab-on-a-chip microfluidic devices automate on-site nucleic acid testing with ultra sensitivity, while electronic noses mimic human olfaction for rapid indicator-free diagnosis [31].

These sensors undoubtably represent paradigm-shifting innovations in plant pathogen detection capabilities. Their ability to diagnose infections up to two weeks before appearance of visible symptoms or spread to wider crops could revolutionize disease management approaches. Early warning would trigger timely, targeted intervention and application of control measures only when newly emerging outbreak threats are confirmed, compared to routine preventative deployment which can mask threats while accelerating pathogen resistance [32]. As such sensors could play a crucial role within sustainable food production systems, reducing chemical inputs through precision application, as well as maintaining productivity to support global food security in the face of evolving pathogen threats. Several success stories of sensors spotting pre-visual signatures of infection or environmental risk factors to deploy preventative treatment highlight future potential [33]. However, barriers around cost, throughput, specificity, infrastructure, commercial availability and critically, user adoption currently inhibit scaled uptake or realization of intended benefits across real-world agricultural settings. Our analysis highlighted lack of correlation between scientific publications on plant pathogen sensors and subsequent adoption, suggesting a disconnect between technology-push innovation pipelines and meeting end-user needs . Progress requires interdisciplinary initiatives bridging engineers, plant scientists, and crucially social scientists to incorporate wider grower requirements and decision-making frameworks around emerging technologies. Insufficient understanding of grower capabilities, perceptions and hesitancies risks creating tools not suited for on-farm realities nor building confidence in using unfamiliar sensors for high-stakes crop protection contexts [34]. Co-development approaches could enhance usability and deliver end-user led innovation pathways improving trust and buy-in. Demonstration farms and participatory training programs would further consolidate knowledge around sensor capacities [35].

Integrating diagnostics with automated treatment application via agricultural drones or robots could overcome labor bottlenecks while minimizing risks around response delays after early infection alerts. Expert systems aggregating and interpreting complex sensor datasets within simple mobile decision-support tools may improve farmer awareness of infection risks and dynamically guide responsible interventions tailored to predicted spread trajectories under local conditions. Effectively harnessing plant pathogen sensors ultimately requires a nexus approach interlinking technological capabilities, infrastructure connectivity, agricultural engineering, regulatory policy, business models, supply chain coordination, and farmer behavioral contexts [36].

This review has synthesized recent progress in diverse sensor technologies moving plant pathogen detection to unprecedented frontiers of speed, sensitivity and crucially earlier pre-visual diagnosis [37]. Their cutting-edge capabilities could overcome limitations constraining legacy approaches relying on late-stage visual symptoms or slow lab-based techniques. Initial examples provide proof-of-concept for enabling sustainable intensification of agricultural production through precisely targeted inputs and minimized crop losses [38]. However fully unlocking and responsibly leveraging the power of these sensors remains a complex multidimensional challenge engaging the full innovation ecosystem. Ongoing interdisciplinary initiatives developing not just laboratory prototypes but field-deployable tools accounting for commercial viability and participatory adoption in local farming contexts will determine the real-world impact emerging sensor technology has on tackling escalating biotic threats [39]. Continued ambitious investments bridging technological capabilities with implementation pathways represent imperative priorities in order to translate next-generation diagnostics into practical plant health management solutions supporting global nutritional security.

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