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Integration of Sensors and Microfluidics in the Battle Against Plant Pathogens: A Technological Perspective

Mei Zhang
Mongolian University of Agriculture and Technology (MUAT), Mongolia

Bat-Erdene Jargal
Department of Biotechnology, Mongolian National University, Mongolia

Abstract

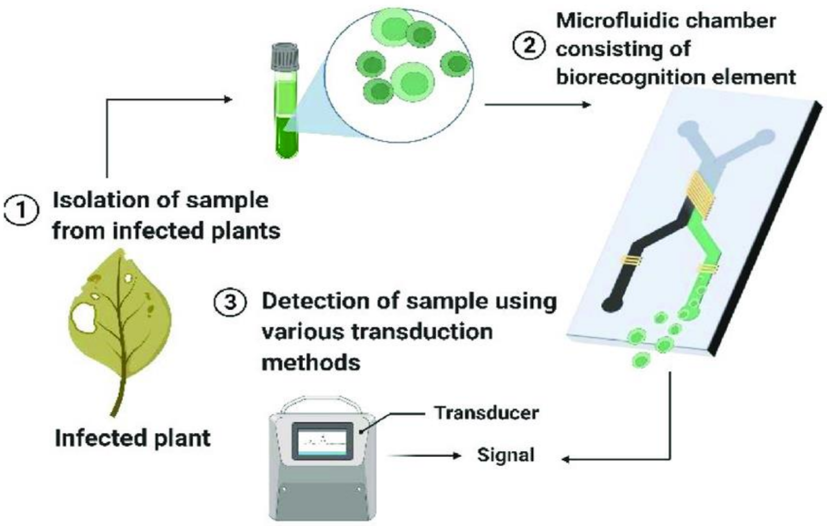
Plant pathogens, including bacteria, fungi, nematodes, oomycetes, and viruses, are a major threat to global agricultural production and food security. The timely detection and monitoring of plant pathogens is critical for effective disease management. Technological advances in sensors and microfluidics have enabled new diagnostic tools for field-based detection and quantification of pathogens. In this article, we provide a comprehensive review of recent developments in sensor and microfluidic technologies that are being integrated into plant pathology and disease management. We discuss various classes of sensors used for plant pathogen diagnostics, including optical, electrochemical, and piezoelectric sensors. We also focus on microfluidic devices known as lab-on-a-chip systems that offer portability, multiplexing, and automation for plant disease diagnostics. Insights are provided into innovative strategies for disease monitoring and control through precise spatial-temporal targeting guided by sensors and microfluidics. The major opportunities and remaining challenges in further integrating these technologies into precision agriculture are also considered. Overall, this review highlights the key role of sensors and microfluidics in accelerating progress against plant pathogens through more precise, rapid, and affordable diagnostics at the point-of-care.

Keywords: *plant pathogens, disease diagnostics, sensors, microfluidics, lab-on-a-chip, precision agriculture, optical sensors, electrochemical sensors*

Introduction

Plant pathogens, including bacteria, fungi, nematodes, oomycetes, and viruses, represent a major threat to global food security, causing devastating yield losses in staple crops. Collectively, plant diseases are estimated to cause economic losses of over $200 billion worldwide each year. Climate change is also exacerbating the spread of plant disease, by increasing overwintering and the range of many pathogens and pests. Traditional methods for plant pathogen diagnostics, such as culturing and molecular assays (e.g. polymerase chain reaction, PCR), are typically laborious, expensive, and time-consuming. These limitations create a critical need for rapid, affordable innovations in plant disease diagnostics to bolster global crop biomonitoring and food security amidst intensifying agricultural pressures in the 21st century.

Figure 1.

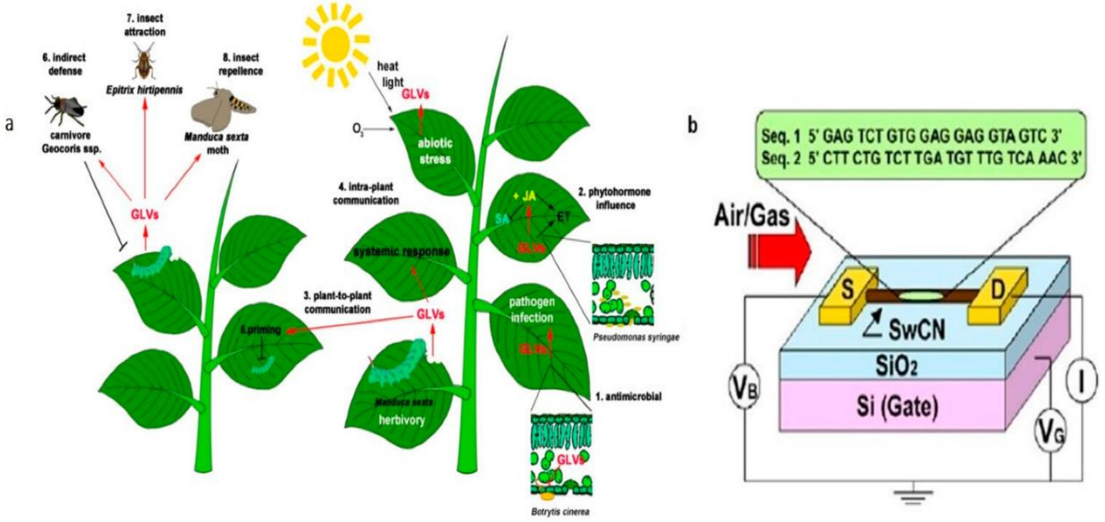


Emerging tools in sensors and microfluidics are poised to transform plant pathogen surveillance and crop protection capabilities. Sensors enable real-time monitoring of plant disease markers or pathogens with high sensitivity and selectivity [1]. Various optical, electrochemical, and piezoelectric sensors have shown tremendous promise for in-field detection of different plant pathogens. Microfluidic "lab-on-a-chip" devices allow streamlined integration of sampling processing, biomarkers extraction and purification, molecular amplification, and optical/electrochemical detection modules onto miniaturized, field-portable cartridges. Microfluidics provide essential sample-to-answer automation, multiplexing, and portability advantages critical for enabling widespread plant molecular testing by growers globally. Additionally, networked sensors feeding spatiotemporal plant health data into geospatial databases can precisely guide targeted delivery of pesticides, biologicals, and other countermeasures onto emerging infectious foci [2].

As innovations continue across disciplines, cross-domain integration of sensors, microfluidics, automation, and data science has disruptive potential to radically advance plant disease forecasting, diagnostics, and control measures. Recent literature has assessed developments in sensors for agriculture , microfluidics for plant research , and precision digital farming. However, a gap persists for comprehensive evaluation of sensors and microfluidics technologies specifically targeting integration into smart plant biosecurity frameworks [3]. In this mini-review, we bridge this key knowledge gap by providing an interdisciplinary perspective regarding incorporation of sensors and microfluidics into next-generation plant disease management systems [4].

We first survey recent advances in specialized sensors for plant pathogen detection and diagnostics, spanning optical, electrochemical, piezoelectric, and other novel platforms. Second, we focus on progress applying microfluidic devices and lab-on-a-chip integration tailored for molecular plant disease assays and field usage [5]. Third, we assess the tremendous upside potential in developing coordinated cyber-agricultural infrastructures that link networked sensing with automated sampling, microfluidic analysis, and targeted real-time delivery of crop protection countermeasures across growth environments. Finally, we examine remaining socioeconomic and technical barriers that must be overcome to achieve broad adoption of integrated plant diagnostic systems, particularly in low resource developing world contexts [6]. Overall, this forward-looking analysis of the crucial intersection between sensors, microfluidics, and plant health monitoring elucidates key innovations driving a paradigm shift towards data-driven smart farming systems able to withstand mounting biotic threats confronting global crop production.

Figure 2.



Numerous factors underscore the urgent impetus for advancing innovative ecosystems at the nexus of sensors, microfluidics, and plant disease management. Most pressingly, endemic plant pests and diseases already cause astronomical economic damage, as annual worldwide crop losses to plant pathogens alone approach $220 billion. These figures will likely intensify as climate change expands overwintering ranges and alters ecologies of numerous devastating pathogens like wheat and coffee rust fungi, late tomato blight infestations, and Huanglongbing citrus greening disease now spreading from Asia to the Americas. Concurrently, unrelenting population growth poses ever-greater demands on agricultural productivity, as an estimated 50% more food must be grown by mid-century to meet nutritional needs [7]. Meeting these agricultural challenges requires transformational progress in plant biosecurity capabilities. Sensors and microfluidics that enable ubiquitous, real-time plant health monitoring to guide precise application of bioprotective measures can provide the nucleus for smart, resilient crop management systems essential for the future. However, unlocking these potential demands deeper collaboration across historically disparate disciplines encompassing plant pathology, biomedical and environmental engineering, diagnostics development, automation, and data science [8]. The integration of sensors and microfluidics tailored for field settings remains in early phases, as innovative tools developed by different groups often remain disconnected rather than built as interoperable solutions [9]. Our analysis herein illuminates crucial gaps and opportunities for further cross-disciplinary ferment at the fertile nexus of sensors, microfluidics, and crop disease management. By elucidating state-of-art technologies, assessing barriers, and identifying high-potential areas for synergy, this forward-looking review seeks to galvanize expanded research and development efforts towards integrated smart farming systems able to meet rising 21st century food security challenges. The stakes for transforming plant pest and disease control capabilities are high. But emerging tools offer grounds for optimism if collaborative spirit and responsible implementation can guide the way forward.

Sensor Technologies for Plant Pathogen Detection

Myriad types of sensors have shown promise for plant disease surveillance, taking advantage of optical, electrochemical, mechanical, thermal and other signals. Here, we briefly survey major categories of sensors that have been explored specifically for plant pathogen detection and diagnostics [10].

Optical sensors: Optical sensors rely on changes in absorbance, fluorescence, reflectance or other measurable optical signals that occur due to the presence of plant pathogens or infection-induced alterations in the host. Colorimetry represents one of the simplest optical sensing modalities, using changes in color for visual quantification of analytes. For instance, Tatagiba et al. developed low-cost paper test strips incorporating gold nanoparticles to visually detect Xanthomonas axonopodis pv. citri, the causative agent of citrus canker, based on DNA-mediated aggregation. Another popular optical approach uses fluorescent tags and quantitative polymerase chain reaction (qPCR) to amplify and detect pathogen DNA, as demonstrated for identification of major potato pathogens including Phytophthora infestans, Potato virus Y, and Potato spindle tuber viroid. Beyond these conventional optics, recent work has applied more advanced techniques like surface plasmon resonance (SPR) and surface-enhanced Raman spectroscopy (SERS) for plant disease detection. SPR sensors measure changes in the refractive index at metal surfaces (typically gold or silver nanoparticles) due to binding events. Li et al. fabricated a multichannel SPR imaging platform to achieve multiplexed detection of wheat stripe rust and powdery mildew [11]. The high specificity of SPR sensors provides major advantages in complex agricultural samples over colorimetry and other simpler optical methods prone to interference. SERS uses amplification of inelastic light scattering by molecules in close proximity to roughened metal nanoparticles. Zhao et al. designed a SERS Nano sensor incorporating silver nanoparticles, aptamers, and graphene oxide to detect fusarium head blight pathogen DNA in wheat with a limit of detection around 1.25 fg/mL. By exploiting plasmonic and spectrally responsive nanomaterials, cutting-edge optical sensors like SPR and SERS are gaining traction in plant disease monitoring [12].

Electrochemical sensors: Electrochemical biosensors couple a biological recognition element (e.g. enzyme, antibody, DNA) to an electrode transducer, converting the biomarker binding event into a readable electrical signal proportional to analyte concentration. These sensors provide rapid, portable, cost-effective detection capabilities, making them well-suited for agriculture field applications [13]. Various electrochemical transduction platforms have been implemented for different plant pathogens, including impedance sensors, field-effect transistors (FETs), voltametric sensors relying on redox reactions, and impedimetric immunosensors based on changes in conductive polymers. For example, Wang et al. developed an ultrasensitive electrochemical biosensor using immobilized DNA probes on gold nanoparticles to detect Ralstonia solanacearum through hybridization-mediated impedance changes with a detection limit down to 33 CFU/mL. Ping et al. designed a FET nano biosensor using antibody functionalized ZnO nanorods to rapidly detect wheat yellow mosaic virus coat protein down to 0.01 ng/mL. Looking forward, wireless electrochemical sensors linked to mobile communication networks and cloud databases will provide valuable spatiotemporal data on plant disease progression necessary for precision digital agriculture [14], [15].

Piezoelectric sensors: Piezoelectric immunosensors measure changes in resonance frequency upon binding of target antigens to antibodies immobilized on a piezoelectric transducer like quartz crystal microbalance (QCM). Liu et al. developed an ultrasensitive QCM nano biosensor using gold nanorod amplification and graphene oxide substrate that could detect the inner envelope membrane protein (IMP) of porcine reproductive and respiratory syndrome virus

(PRRSV) down to 2.7 pg/mL within 6 minutes. By measuring microscale changes in mass and viscoelasticity, piezoelectric sensors have also proven useful for detection of bacterial and fungal plant pathogens. For example, Torres et al. used QCM immunosensors for sensitive impedance-based detection of Candidates Liberibacter asiaticus, causal agent of the devastating citrus disease Huanglongbing (HLB). The high stability, specificity, and rapid response of piezoelectric sensors gives them distinct advantages for precision agriculture monitoring of plant pathogen dynamics [16].

Other types: thermal, MEMS, biomimetic: Beyond optical and electrochemical modalities, various other sensing platforms have shown initial promise for plant disease applications but remain less explored to date. For instance, Liao et al. devised an infrared thermal sensor coupled to a neural network model able to detect Huanglongbing infection across citrus cultivars with ~95% accuracy, taking advantage of subtle alterations in leaf temperature patterns. Sophisticated microelectromechanical systems (MEMS) have been incorporated into plant pathogen sensors, such as using suspended microcantilevers functionalized with antibodies or aptamers to enable nanoscale detection of molecules by changes in surface stress. Finally, biologically inspired or biomimetic sensors aim to replicate recognition and signaling mechanisms in nature. Kamande et al. described a synthetic biology approach using transgenic tobacco cells to produce a luminescent reporter triggered by potato virus Y infection, essentially creating a plant-based biosensor [17]. Further development of such innovative sensor designs could provide new routes to track plant pathogen dynamics [18].

Microfluidic Devices for Plant Disease Diagnostics

In parallel with rapid advances in sensors tailored for plant pathogens, progress has also been made applying microfluidic technologies to agricultural challenges. Microfluidic devices enable precise manipulation of fluids at sub-millimeter scale using channels and chambers engineered from glass, polymers, paper, or gels. The field of microfluidics offers game-changing potential for bringing rapid, affordable molecular testing for plant diseases to point-of-need locations in the field.

Microfluidic sample processing: One essential application of microfluidics for agriculture diagnostics is streamlining tedious sample processing steps like pathogen isolation and nucleic acid extraction. For example, Kao et al. described an automated microfluidic platform using magnetic beads for simultaneous RNA/DNA purification from eight plant and livestock samples in just 40 minutes. Dutta et al. developed a microfluidic chip using laminar micro vortices for efficient isolation, lysis and molecular detection of Ralstonia solanacearum cells from complex soil bacteria mixtures. By integrating sample cleanup on microfluidic cartridges, the groundwork can be laid for simplified molecular testing outside laboratory settings [19].

Isothermal nucleic acid amplification: A major recent advance for point-of-care plant pathology has been implementation of isothermal microfluidic devices to enable DNA/RNA amplification without thermocycling equipment. Notable examples include loop-mediated amplification (LAMP) and recombinase polymerase amplification (RPA), which use displacement enzymes and primers to rapidly amplify target sequences under isothermal conditions (~60-65°C). Tsoung et al. designed a portable RPA microfluidic chip for visual fluorescent detection of Acidovorax citrulli, achieving rapid and specific on-site diagnosis of bacterial fruit blotch in cucurbits. Similarly, Amer et al. developed microfluidic RPA chips using inkjet-printed reagents to identify major cotton pathogens (Xanthomonas citri pv. malvacearum, Colletotrichum gossypii var. cephalosporioides) and races of Fusarium oxysporum f. sp. Vasinfectum [20]. This pioneering microfluidics avoid cumbersome thermocyclers, expanding access to molecular plant testing.

Lab-on-chip integration: Ultimately, microfluidic biosensors aim to fully integrate pathogen sampling, biomarkers extraction and purification, molecular amplification, and optical/electrochemical detection on miniaturized printable chips. These lab-on-a-chip devices offer field portability, short analysis times, and potential for high-throughput sample multiplexing. For example, Lui et al. developed an integrated polymer microfluidic chip using loop-mediated isothermal amplification (LAMP) combined with an opt magnetic biosensor, achieving detection limits around 100 CFU/mL for the bacterial rice pathogen Xanthomonas oryzae pv. oryzae. Similarly, Ruszkowski et al. designed a multifunctional microfluidic system for isothermal LAMP amplification and colorimetric detection of Phytophthora pathogens in ornamentals. Further innovation is still needed to optimize full sample-to-answer integration. But looking forward, standardized microfluidic plant diagnostic cartridges could be revolutionary for on-site quality inspection and disease monitoring [21].

Precision Agriculture Systems: Coordinating Sensors, Microfluidics, and Disease Control

While sensors and microfluidics each bring distinct advantages for plant health monitoring, integrating these technologies into coordinated agricultural frameworks could be transformative. Networked systems that leverage GPS, aerial imaging, and real-time environmental data from distributed sensors can generate predictive risk models and richly mapped surveillance of plant pathogen spread across growth areas and farming regions. This spatiotemporal understanding fed into geospatial databases can then guide targeted delivery of fungicides, bactericides, or biological control agents precisely onto emerging infectious foci using automated microfluidic sprayers or drones [22].

Automated tissue sampling coordinated by such surveillance networks likewise enables intensive, large-scale screening efforts using multiplexed microfluidic analysis or next-generation sequencing assays. These big data streams can accelerate identification of quantitative trait loci or epigenetic biomarkers to speed breeding of disease-resistant cultivars. As innovations continue, integrated cyber-physical architectures tightly linking environmental monitoring, diagnostics data, and intervention delivery could provide a paradigm shift for tackling endemic plant pathogens across vast farming landscapes.

Early proof-of-concept work has validated the utility of coordinated sensor-microfluidic solutions for precision plant disease control. For example, Sandhu et al. designed a robotic sensory system incorporating pathogen DNA quantification, aerial imaging, and spatial mapping to target herbicide spraying, achieving effective weed management with ~75% less herbicide usage. Looking forward, companies are actively developing integrated sensor-spraying systems for precision agriculture, like Teralytic's nano-sensor networks linked to smart sprayers that enable fungicide application specifically onto infected vines in vineyards based on microclimate monitoring [23].

While considerable progress has been made, fully realizing integrated predictive modelling and outbreak response capabilities requires expanding sensing and microfluidic testing infrastructure. Affordable, field-rugged sensor networks must be broadly deployed to provide rich temporal and geospatial disease datasets. Handheld or drone-based spectrometers likewise show promise for rapid proximal crop sensing. These could feed hyperspectral survey data to trajectory models forecasting infection fronts. In tandem, widespread access to molecular and meta-omic profiling on microfluidic cartridges would enable ubiquitous screening to identify resistant plant variants. Identifying optimal network architectures and interfaces allowing fluid data consolidation remains an area needing focused collaboration across disciplines [24].

Importantly, successful integration requires overcoming barriers beyond just technical constraints. Standardized communication protocols and data formats are essential for seamless operability and automation between modules. Development costs for sensor systems and microfluidic cartridges also remain prohibitively high for scale-up in low-resource agricultural settings [25]. Overcoming connectivity limitations and achieving truly democratized precision agriculture will rely on focused efforts tailoring affordable innovations for Global South smallholder farmers most vulnerable to endemic plant diseases [26]. Additionally, coordinated sensing-intervention networks warrant careful implementation to avoid risks like accelerated pest resistance or negative environmental impacts from excessive agrochemical usage. Integrating real-time resistance profiling and sustainable integrated pest management philosophy into automation routines can help guide responsible innovation. Policy foresight and international partnerships can further steward equitable access to precision technologies across the digitally divided agriculture sector. But looking forward, well-designed integration of sensing, diagnostics, modelling and automated intelligent crop protection measures offers enormous economic and social benefit safeguarding global food security. With a concerted push across disciplines, the essential components for transformative smart safety nets guarding crops worldwide appear increasingly within reach [27].

Remaining Challenges and Outlook

While major progress has been made applying sensors and microfluidics to combat plant diseases, various constraints still limit widespread adoption and additional innovation is vital. Key remaining challenges include:

(1) Integration of emerging technologies like CRISPR diagnostics, synthetic biology sensors, and multiplexed meta-omics profiling on microfluidic platforms.

(2) Optimization for complex field samples: removal of inhibitors, selectivity in heterogeneous matrices

(3) Network communication protocols and data standardization

(4) Cost reductions for mass agricultural implementation in low-resource settings

(5) Seamless connectivity across the diagnostic testing workflow from sample-to-answer and real-time decision support

Further cross-disciplinary collaboration spanning plant pathology, microfluidics, electronics, and automation engineering can help address these barriers. As technology continues advancing in parallel with pressures from climate change and food security demands, researchers must keep exploring innovative ways to leverage sensors, microfluidics, robotics, and informatics [28]. These emerging tools can provide the nucleus for smarter, automated plant biosecurity networks essential to safeguard agricultural production for the future.

Conclusions

Integrated sensors and microfluidic platforms offer disruptive potential to accelerate plant disease detection and precision crop protection capabilities. We have reviewed major directions in optical, electrochemical, and piezoelectric sensors tailored for plant pathogen monitoring. Progress in microfluidic sample processing, isothermal amplification, and lab-on-a-chip integration has also shown considerable promise to bring rapid molecular testing nearer to the field. Translating these technologies into coordinated frameworks for spatiotemporal disease mapping and targeted application of countermeasures is a critical next phase. As innovation continues at this crucial convergence of plant health and emerging biotechnology, sensors and microfluidics are poised to provide groundbreaking new solutions in humanity’s continual fight against crop disease [29].

The urgent need for improved plant disease diagnostics and monitoring is clear in light of the existential threats posed by food insecurity and climate change in the 21st century. Plant pathogens are estimated to claim 10-16% of the global harvest each year, and the increasing frequency of extreme weather events coupled with altered pathogen and vector ecologies under climate change exacerbate risks of impactful disease epidemics. Existing surveillance networks have critical blind spots, especially in the developing world, while traditional diagnostic methods involving culturing or molecular testing like PCR and ELISA remain too expensive, time-consuming, and labor-intensive for widespread adoption. The integration of sensors and microfluidics can help overcome many limitations holding back progress, through rapid in-field detection capabilities and streamlined sample-to-answer molecular analysis [30].

Key innovations on the horizon involve comprehensive lab-on-chip microfluidic devices incorporating nucleic acid extraction, isothermal amplification, and optical/electrochemical detection modules to provide sample-in, answer-out plant pathogen analysis. For example, Amer et al. recently reported an integrated inkjet-printed microfluidic chip able to perform RNA/DNA extraction, reverse transcription RPA, and lateral flow visualization for sensitive on-site detection of cotton bacterial blight [31]. Similar integrated microfluidic plant diagnostic systems have been designed using LAMP-optical detection, RPA-electrical sensing, and more. The continued miniaturization and coordination of these “chemical laboratories” onto portable, field-deployable cartridges could revolutionize how plant disease screening is performed globally. In tandem, ever-advancing multiplexed nucleic acid sequencing and meta-omics profiling on microfluidic devices will enable even finer-grained understanding of plant-pathogen-environment interactions over space and time [32].

Networked sensing technologies feeding such integrated microfluidic analysis data into geospatial cloud databases can then guide highly targeted application of pesticides, biologicals, gene editing treatments, and other countermeasures precisely to emerging disease infection fronts. Examples like the robotic sensory-spraying system designed by Sandhu et al. that coordinates weed mapping and herbicide delivery illustrate the enormous potential upside in efficiently mitigating biotic threats while minimizing unnecessary agrochemical usage. As innovations in sensors, automation, and data science continue, coordinated cyber-agricultural infrastructures leveraging massive streams of environmental surveillance data could radically transform how endemic plant pathogens are managed across vast farming landscapes. Extending these interconnected biomonitoring and treatment delivery frameworks through international partnerships and satellite-based remote sensing could also provide invaluable early warning systems and inform transboundary policymaking against devastating diseases like wheat rusts, late blight, and citrus greening emerging as climate change expand pathogen ranges globally.

Ultimately, realizing the full promise in smart integrated plant disease management networks requires holistic consideration of socioeconomic barriers beyond just technical constraints. Affordability and access limitations in the developing world must be central in driving product development of microfluidic devices and sensor networks tailored for agriculture. Connectivity issues similarly demand innovation, considering the remote rural contexts farming often operates within globally. Requisite computing infrastructure, plant health data standards, and personnel training add further complications in broadly establishing coordinated systems. Moreover, potential risks from heightened agrochemical usage guided by precision spraying regimes emphasize the need for caution by integrating resistance monitoring and sustainable integrated pest management philosophy. Policy measures like subsidy programs and international partnerships can help promote rapid large-scale adoption of emerging technologies by agriculture worldwide. With conscientious implementation that provides for the needs of low-resource farmers and emphasizes environmental stewardship, the responsible development of sensor-microfluidic infrastructures for data-driven crop protection promises enormous societal benefit safeguarding global food security.

The integrative analysis presented here aims to spur expanded cross-disciplinary efforts at the intersection of plant health, diagnostics, automation, and data science. As sensors, microfluidics, networking, and analytical tools continue rapidly innovating in parallel with intensifying pressures on agriculture, researchers across fields must keep exploring creative ways to harness emerging technologies for combating endemic plant diseases [33]. The collective progress reviewed herein highlights the tremendous near-term potential to transform plant pathogen surveillance, mapping, and control capabilities if innovative tools are branched across disciplines. Widespread adoption of integrated sensor-microfluidic solutions into standardized, field-deployable modular platforms can provide the next wave of growth allowing smarter, automated plant biosecurity frameworks to take root globally. Such coordinated diagnostics-intervention networks will in turn supply the nucleus enabling data-driven digital agriculture to reach full fruition managing crop diseases amidst the demands and uncertainties of the 21st century. With focused innovation connecting all facets of the plant health technology pipeline, transformative leaps in tackling these grand challenges appear within reach [34].

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