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Plant Protection : Technologies redefined

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ABSTRACT

Although historically effective, traditional crop protection approaches are increasingly limited by resistance development, environmental concerns, and regulatory constraints. These challenges highlight the urgent need for innovative, sustainable, and technologically advanced solutions. Emerging tools, such as nanoformulations, biotechnological innovations, secondary metabolites, low-dose pesticides, biosensors, and artificial intelligence, have demonstrated substantial promise in reshaping modern crop protection strategies. As global agricultural systems continue to evolve, the integration of these technologies within holistic frameworks such as IPM and climate-smart agriculture will be essential. However, ensuring widespread adoption requires addressing challenges such as regulatory gaps, production scalability, field performance variability, and farmer accessibility. Continued investment in research, capacity building, and science-driven policy development is vital for accelerating innovation and ensuring that these technologies are translated into practical solutions. Ultimately, the convergence of biological, digital, and nanotechnological advancements holds the potential to safeguard crop health, support sustainable agriculture, and strengthen global food security.

Keywords : Integrated pest management, Nanoformulations, Artificial intelligence, Biosensors, Sustainable agriculture.

Introduction

Global agriculture is undergoing a major transformation as it faces the dual challenge of feeding a rapidly growing population and sustaining the environment. With the world's population expected to reach 9.2 billion by 2050, food production must increase by an estimated 70% to meet future needs. According to recent statistics, nearly 50% of usable land is dedicated to agriculture, but productivity remains a major challenge. Losses to agriculture remain substantial, as biotic and abiotic stresses account for approximately 40% of the yield reduction worldwide (Kubiak *et al.*, 2022). Abiotic stresses include extreme temperatures, water and nutrient scarcity, salinity, pollution, and soil degradation, whereas biotic stresses involve pathogens, insects, nematodes, rodents, birds, mammals, and weeds. Climate change exacerbates these constraints by altering pest populations, increasing the frequency of extreme weather events, and accelerating the

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environmental degradation. As global attention intensifies on climate mitigation and ecosystem health, agricultural systems are under increased scrutiny regarding their ecological impacts. For instance, in the European Union, reducing the environmental footprint of the food system has become a pillar of the Green Deal policy. Considerable efforts have been made over the past few decades by crop protection organizations and academics worldwide to discover new technologies.

Crop protection involves a diverse set of tools, technologies, and practices designed to safeguard crops. Over time, innovations in fertilizers, pesticides, mechanization, and plant breeding have allowed modern farms to produce food for the majority of the population. This shift has been supported by major breakthroughs in agricultural inputs, mainly through the use of synthetic fertilizers and pesticides. The mandatory use of these inputs has reduced long-term resilience and contributed to the resistance of pathogens and environmental harm. Simultaneously, the catapulting challenges have increased the need for new solutions. Recent advances in innovation models, discovery tools, and crop technologies are driving the development of safer and more sustainable crop protection strategies (Sanyeì-Mengual *et al.*, 2022). Innovations such as nanotechnology, RNA interference (RNAi), CRISPR-based tools, biopesticides, genetically modified resistant crops, and precision agriculture are increasingly being integrated into modern agricultural practices to enhance efficiency and reduce reliance on conventional chemical pesticides (Chen, 2025). This article aims to address the pressing concerns and challenges of the agricultural industry by highlighting recent interventions in crop protection.

Conventional Agricultural Practices

Conventional agricultural practices have been employed to manage plant diseases and reduce the spread of pathogens. These include field sanitation, legal and quarantine measures, use of resistant varieties, crop rotation, intercropping, soil solarization, biofumigation, soil amendments, anaerobic soil disinfection, steam sterilization, and soilless cultivation methods. Field sanitation focuses on minimizing favorable conditions for pathogen development by regulating canopy humidity, removing infected plant residues and weeds, and disinfecting tools and equipment. Legal and quarantine measures help prevent the long-distance spread of pathogens through contaminated planting materials, seeds, and packaging (Yadav *et al.*, 2022). The development of resistant cultivars has been an effective disease management strategy, particularly against soil-borne pathogens such as *Fusarium oxysporum* in tomato plants. Cropping systems, such as rotation and intercropping, disrupt pathogen life cycles, improve soil health, and reduce the incidence of disease epidemics. Additional approaches, including soil solarization, deep tillage, biofumigation using *Brassicaceae* cover crops, steam sterilization, and organic amendments, help suppress soil-borne pathogens by improving soil physicochemical properties and promoting the growth of beneficial microbial communities (Baysal-Gurel *et al.*, 2018).

Despite their effectiveness, conventional agricultural practices have several limitations that restrict sustainability and efficiency. Many of these methods are primarily effective against soil-borne pathogens and are less successful in managing pathogens with wide host ranges. Their success is highly dependent on climatic conditions, soil type, pH, organic matter content, and other physicochemical properties, resulting in inconsistent outcomes. Moreover, these approaches are often labor-intensive, time-consuming, and energy-demanding, thereby reducing their practical adoption by farmers. Some practices, such as biofumigation with *Brassica* crops, may increase phytotoxicity and disease severity under certain conditions (El-Sharouny *et al.*, 2015). Given the rising global population and significant annual crop losses due to plant diseases, conventional methods alone are insufficient to achieve the yield gains required for ensuring food security.

Novel Technologies in Crop Protection

Nanoformulations

Nanotechnology-based formulations enable advanced disease management strategies that improve efficacy and selectivity beyond those of conventional methods. Nanoformulations (1–100 nm) utilize surface-dominated properties, which significantly improve the solubility, stability, and controlled release of active ingredients in the body. Chemical dependency can be reduced by encapsulating or conjugating these active ingredients in polymeric, lipid, inorganic, or hybrid nanocarriers. Nanoformulations can act in two principal ways: (i) as nanopesticides, in which the nanomaterial itself is biologically active, and (ii) as nanoscale delivery systems for conventional or biologically active ingredients.

Metallic and metal-oxide nanoparticles, such as silver (Ag), copper (II) oxide (CuO), zinc oxide (ZnO), magnesium oxide (MgO), titanium dioxide (TiO_2), and cerium dioxide (CeO_2), display intrinsic broad-spectrum antimicrobial properties against pathogens. They employ mechanisms that include membrane disruption, generation of reactive oxygen species (ROS), interference with ATP synthesis and damage to DNA and key enzymes. These nanoparticles can suppress important diseases, such as bacterial blight, soft rot, wilt, sheath blight, and various fruit rots, at comparatively low doses. When used as carriers, nanostructured materials such as chitosan, alginate, polycaprolactone, silica, and mesoporous silica can encapsulate conventional fungicides or insecticides, enhancing their stability and ensuring stimulus-responsive release at the site of infection. Controlled delivery minimizes off-target losses through leaching, runoff, and volatilization, thereby reducing the overall pesticide usage while maintaining crop health (Ray *et al.*, 2023). Nanoformulations also open new frontiers in precision plant protection through the smart delivery of nucleic acids and improved diagnostics. Engineered nanoparticles can carry double-stranded RNA, small interfering RNA, or other nucleotides into plant parts to facilitate gene silencing in pathogens. Nanomaterials (gold nanoparticles, quantum dots, carbon nanotubes, and graphene derivatives) have been integrated into biosensors, bio-barcode assays, and nanopore-based platforms for the rapid and sensitive detection of phytopathogens and their volatiles. These technologies aid in early disease detection, which supports timely intervention (Cardoso *et al.*, 2022).

Nanoformulations provide strong technical benefits but raise significant environmental and regulatory concerns. Their small size and high reactivity allow them to interact with soil and biota, where they can disrupt beneficial microbes and nutrient cycles and may exhibit phytotoxic effects on plants. Biogenic nanomaterials can reduce some risks; however, standardized ecotoxicity tests, long-term field data, clear regulatory categories, scaling up production, and building farmer awareness remain major challenges (Mushtaq *et al.*, 2020). If these barriers are addressed, nanoformulations could support the precise, low-dose, and environmentally compatible protection of crops in IPM systems.

Low Doses Pesticides

The intensification of global agriculture has led to the annual use of approximately 2 million tons of pesticides to combat diverse pest pressures that threaten crop yield and quality (Sharma *et al.*, 2019). The indiscriminate use of pesticides promotes resistance in target pests and causes ecological disruption, such as biodiversity loss, food web contamination, and soil microbiome disturbance.

Low-dose pesticide strategies aim to minimize chemical inputs by using the minimum effective dose, thereby reducing application rates while still achieving effective pest inhibition and yield protection (Vandenberg *et al.*, 2012). This approach is grounded in determining the "minimum effective dose" through stringent laboratory and multi-location field trials. This approach reduces the selection pressure that drives resistance development in pest populations while simultaneously minimizing non-target toxicity and overall farm input costs. For example, the use of low-dose azoxystrobin and tebuconazole in cereals for disease control and seed treatment with low-dose neonicotinoids, such as imidacloprid in cotton and maize, has successfully managed pests (Parizadeh *et al.*, 2021). Furthermore, modeling and empirical data from Muniz-Junior *et al.* (2023) confirmed that integrating low-dose pesticides with complementary control measures effectively slows resistance evolution without compromising the efficacy. When incorporated into IPM, low-dose applications align with ecological goals, meet regulatory residue limits, and cater to market demands for safer produce.

Biotechnological Approaches

Biotechnology has become a transformative force in modern agriculture, with innovative strategies for protecting crops from pests, diseases, and environmental stresses. By integrating tools such as genetic engineering, gene editing, molecular diagnostics, and bioinformatics, biotechnology enables the development of resistant crop varieties and supports sustainable crop protection practices (Anand, 2017). One major contribution of biotechnology to crop protection is the development of genetically modified organisms (GMOs). Techniques such as CRISPR–Cas9, Agrobacterium-mediated transformation, and particle bombardment have enabled the insertion or modification of genes associated with biotic and abiotic stress resistance (Lassoued *et al.*, 2019).

In rice, CRISPR/Cas9-mediated editing of stress/abscisic acid-activated protein kinase 2 (SAPK2) significantly enhanced drought tolerance by regulating ABA signaling and stomatal closure, thereby improving water-use efficiency (Lou *et al.*, 2017). In wheat, multiplex genome editing using CRISPR/Cas9 has enabled the simultaneous modification of multiple homoeologous genes associated with stress sensitivity, contributing to enhanced tolerance to drought and salinity (Wang *et al.*, 2018). In tomatoes, CRISPR/Cas9-mediated mutation of SlMAPK3 improved heat stress tolerance by regulating reactive oxygen species (ROS) scavenging and heat shock protein expression (Li *et al.*, 2019). Furthermore, editing of transcription factors, such as ethylene-responsive factor (ERF) genes, in various crops has demonstrated improved tolerance to drought and salinity through the regulation of downstream stress-responsive genes (Debbarma *et al.*, 2019). Similarly, virus-resistant papaya and late-blight-resistant potatoes demonstrate how precise genetic interventions can protect crops from devastating diseases.

Molecular markers also play a vital role in accelerating the identification and selection of resistance traits. Marker-assisted selection (MAS) has enabled breeders to track genes linked to disease resistance, stress tolerance, and improved nutrient use long before traits are visible in the fields (Paril *et al.*, 2024). DNA markers, such as single nucleotide polymorphisms (SNPs), simple sequence repeats (SSRs), and amplified fragment length polymorphisms (AFLPs), support gene pyramiding to build durable and multi-gene resistance against evolving pathogens (Parmar *et al.*, 2017). They also aid in the development of drought-, salt-, and heat-tolerant crops by identifying genes associated with water-use efficiency, osmotic balance, and protective stress proteins (Anwar *et al.*, 2024). Despite significant advancements, biotechnology faces challenges, including public concerns, regulatory constraints, and debates regarding the acceptability of GMO-related tools in agriculture (Osendarp *et al.*, 2021). Continued research, transparent communication, and responsible regulation are essential to balance innovation, safety, and public trust (Shimatani *et al.*, 2017).

RNA Interference

RNA interference (RNAi) is a next-generation technology that can address these challenges owing to its high specificity, biodegradability, and minimal off-target effects. By promoting gene silencing mechanisms, RNAi provides an unprecedented ability to target essential pest and pathogen genes in agricultural fields. RNAi operates through the introduction of double-stranded RNA (dsRNA), which is processed into small interfering RNAs (siRNAs) that guide the degradation of complementary mRNA. The two primary approaches for implementing RNAi are Host-Induced Gene Silencing (HIGS) and Spray-Induced Gene Silencing (SIGS). HIGS involves transgenic plants that produce dsRNA internally, enabling continuous and systemic protection, whereas SIGS relies on externally applied dsRNA formulations that are absorbed by pests, pathogens and plant tissues. Significant progress has been made in applying RNAi to a broad range of agricultural threats. For example, dsRNA sprays have been tested against lepidopteran pests, rust fungi, and viral vectors, demonstrating effective pest mortality and disease suppression (Werner *et al.*, 2020).

However, a major barrier to widespread adoption is the instability of naked dsRNA under field conditions, as it is rapidly degraded by environmental nucleases, UV radiation, and microbial activity, thereby reducing its efficacy in open field applications. To address this challenge, a range of engineered delivery platforms have been developed, greatly improving the stability, persistence, and cellular uptake of dsRNA in plants and other target organisms. However, several constraints must be addressed before RNAi-based biopesticides can be commercialized. Regulatory frameworks for dsRNA products are still emerging, and evaluation guidelines for environmental fate, nontarget effects, and biosafety require further development. Production scalability and formulation costs also pose challenges, as commercial volumes of high-purity dsRNA must be generated at economically feasible levels for field applications.

Mycoviruses

Mycoviruses are viruses that infect fungi and are increasingly recognized as important biological regulators with a strong potential for crop protection. Many mycoviruses naturally alter the pathogenicity of their fungal hosts, and those that induce hypovirulence can significantly weaken plant pathogenic fungi, making them valuable biocontrol agents. An increasing number of mycoviruses that induce fungal hypovirulence from a wide variety of taxonomic groups have been reported (García-Pedrajas *et al.*, 2019). Their application in disease management largely depends on their ability to move through natural pathogen populations.

Several examples demonstrated the potential: a chrysovirus-like mycovirus (FgV-ch9) reduces the virulence of *Fusarium graminearum*, the causal agent of *Fusarium* head blight; the chrysovirus FodV1 diminishes the pathogenicity of *F. oxysporum* in carnation; and PtCV1, isolated *from Pestalotiopsis theae*, completely suppresses the virulence of fungus and even converts it into a non-pathogenic endophyte on tea (Zou *et al.*, 2024). In some cases, mycoviruses enhance fungal RNAi activity, particularly in the absence of viral suppressors of RNA silencing (VSRs). These conditions strengthen the endogenous RNAi machinery and may improve the efficacy of externally applied dsRNA in the fungi.

The practical use of mycoviruses for crop protection faces several challenges. Many mycoviruses cause latent or mild infections, making their effects on virulence inconsistent or host-dependent. Environmental factors, such as temperature and host physiology, can further influence the stability and ability of these factors to induce hypovirulence. Moreover, the large-scale production, delivery, and field application of mycovirus-infected fungal strains remain technically challenging and poorly standardized processes. Regulatory uncertainties and biosafety concerns regarding the release of virus-infected fungi into agricultural ecosystems also present formidable obstacles.

Bacteriophages

Bacteriophages are highly host-specific viruses that infect specific bacterial strains through precise interactions between phage surface proteins and bacterial receptors. They are present throughout ecosystems and are considered the most abundant biological entity on Earth. Phages display extensive structural and genetic diversity, ranging from tailed icosahedral to tailless and filamentous forms. Their genetic material may be DNA- or RNA-based, and many possess enzymes, such as depolymerases, that enable them to degrade bacterial biofilms (Rao *et al.*, 2023).

Phages follow lytic, lysogenic, or chronic life cycles; however, lytic phages are key to crop protection because they rapidly replicate inside bacterial cells and cause bacterial cell lysis. It is effective in suppressing harmful plant pathogens, including those resistant to pesticides and antibiotics (Ranveer *et al.*, 2024). However, bacteria can evolve resistance via strategies such as altering receptors, CRISPR–Cas immunity, restriction–modification systems, abortive infection pathways, and superinfection exclusion (McGee *et al.*, 2023). To counter this, researchers have employed phage cocktails, phage cycling, and genetically engineered phages designed to bypass bacterial defenses and target essential bacterial functions (Liu *et al.*, 2023).

In agricultural systems, phages function as targeted biocontrol agents against significant bacterial pathogens, including *Xanthomonas*, *Pseudomonas*, *Ralstonia*, and *Erwinia*. Applications in crops, such as stone fruits, tomatoes, peppers, grapes, citrus, and soybeans, have demonstrated reductions in disease severity and improvements in plant health (Garvey, 2022). Their delivery through foliar sprays, seed coatings, soil drenches, and irrigation systems increases flexibility, whereas protective formulation technologies, such as UV stabilizers and encapsulation polymers, have improved persistence under field conditions (Nawaz *et al.*, 2023). In addition to controlling foliar pathogens, phages contribute to soil health by shaping microbial communities and reducing pathogenic bacteria without harming the beneficial microbiota. This activity supports nutrient cycling and enhances plant resistance to environmental stress (Gildea *et al.*, 2022). Phages are in accordance with climate-smart and sustainable agriculture because of their specificity, environmental safety, biodegradability, and ability to co-evolve with pathogens (Holtappels *et al.*, 2021). Their production is economical and scalable, offering particular value to farmers in regions where climate change intensifies bacterial disease pressure (Nawaz *et al.*, 2023). Adoption is limited by environmental sensitivity (e.g., UV radiation), inconsistent field performance, regulatory uncertainty, and the need for farmer training (Gildea *et al.*, 2022).

Advances in genomics, metagenomics, and synthetic biology have accelerated the discovery and engineering of phages with improved host range, stability, and biocontrol efficacy (Kasman and Porter, 2022). The integration of phages with beneficial microbes, biological pesticides, and broader Integrated Pest Management (IPM) frameworks promises more robust and climate-resilient disease management strategies (Villalpando-Aguilar *et al.*, 2022). As regulatory frameworks mature and field technologies evolve, phages are poised to become key components of environmentally sustainable crop-protection systems.

Secondary Metabolites

Despite the global reliance on synthetic pesticides, increasing concerns regarding chemical pollution, phytotoxicity, and the evolution of pesticide-resistant pests have intensified the interest in natural, eco-friendly defense strategies. Secondary metabolites constitute a diverse group of plant- and microbe-derived compounds that play a central role in defense against biotic and abiotic stresses. Key defensive compounds, such as alkaloids, tannins, and flavonoids, control the growth of invading microbes (Lobiuc *et al.*, 2023). Advances in genomics and molecular biology have facilitated the discovery of biosynthetic gene clusters, activation of silent pathways, and engineering of codon-optimized metabolic routes, thereby enhancing secondary metabolite production. These innovations support the sustainable exploitation of both plant- and microbe-derived secondary metabolites for agricultural applications.

Among microbial sources, Trichoderma species stand out as powerful biological control agents that synthesize a wide range of bioactive secondary metabolites, including peptaibols, terpenoids, and pyrones. These metabolites restrain pathogenic fungi and bacteria by disrupting their membrane integrity or inhibiting their growth (Zhang *et al.*, 2022). Many *Trichoderma* metabolites activate plant immune responses, such as Systemic Acquired Resistance (SAR) and Induced Systemic Resistance (ISR), enhancing plant resistance beyond direct antimicrobial effects. *Bacillus* species produce several secondary metabolites, including lipopeptides such as iturins, fengycins, and surfactins, which exhibit potent antifungal and antibacterial activities. These compounds disrupt pathogen cell membranes, inhibit spore germination, and disease development in crops. *Bacillus* synthesizes polyketides, volatile organic compounds, and antimicrobial peptides that contribute to biocontrol.

However, field applications remain constrained by strain variability, environmental influences, and an incomplete understanding of metabolite regulatory pathways. A comprehensive analysis is still lacking; however, tools such as VOSviewer and Bibliometrix offer opportunities for mapping research progress and identifying knowledge gaps (Aria and Cuccurullo, 2017).

Biosensors

Early detection of pests and diseases is essential for timely intervention and effective disease management to prevent crop losses. Traditional pathogen identification methods, such as visual assessment, culture-based assays, enzyme-linked immunosorbent assay (ELISA), polymerase chain reaction (PCR), and loop-mediated isothermal amplification (LAMP), which are widely used, often lack speed, specificity, and field portability. Biosensor technologies address these gaps and empower growers to make timely and informed decisions to minimize crop losses and reduce their dependence on chemical interventions.

A biosensor typically integrates a specific biological recognition element (antibodies, DNA probes, enzymes, or aptamers) with a physicochemical transducer capable of converting a molecular signal into a quantifiable result (electrochemical, optical, thermal, or piezoelectric signal). Among these, electrochemical and optical biosensors have been more widely applied in plant disease management. Electrochemical biosensors can detect pathogens in various sample types, such as air, water, soil, seeds, and foliage, through molecular recognition on electrode surfaces. Techniques such as electrochemical impedance spectroscopy (EIS), quartz crystal microbalance (QCM), and voltammetry allow the quantification of pathogen-specific DNA, RNA, or antigens with high sensitivity. Prominent developments include microfluidic electrochemical immunosensors for the in-field detection of bacterial and viral pathogens, DNA-probe-based voltammetric sensors for phytoplasmas and mosaic viruses, and nanoparticle-enhanced biosensors for fungi and bacteria (Narware *et al.*, 2025). Optical biosensors provide another critical capability: the measurement of binding interactions using changes in the amplitude, phase, or frequency of the emitted light. Lateral flow immunoassays (LFIA), often using gold nanoparticles, are now ubiquitous as paper-based point-of-care tests for pathogens. Surface plasmon resonance and fluorescence-based biosensors have been developed for multiplexing and high-throughput screening, further advancing the diagnostic capacity for field applications (Zhang *et al.*, 2024).

In situ diagnosis facilitated by biosensors allows targeted pesticide or fungicide application, thereby reducing environmental contamination and minimizing the selection pressure for resistant pathogens. Real-time pathogen surveillance supports precision IPM, which is delivered on mobile devices or through wirelessly connected farm networks. Integration with nanotechnology and the IoT has enabled biosensors to become smaller, more sensitive, and easier to deploy. Advances in microfluidics and sample preparation (e.g., magnetic bead extraction) have helped overcome field-specific challenges, such as matrix interference and low target abundance.

The major challenges in biosensor advancements are the development of biosensor platforms for routine field use, including sample handling, environmental stability, cost, validation across diverse crops/patho systems, and end-user adoption of the technology. Efforts to increase multiplexing capabilities, reduce sample-to-result times, and automate data interpretation will accelerate biosensor use in agriculture. In the future, biosensor-guided predictive modeling for disease forecasting and risk management is likely to improve the productivity and sustainability of crops.

Artificial Intelligence

Artificial Intelligence (AI) has emerged as a pivotal technological advancement in modern phytopathology, allowing rapid, accurate, and scalable solutions for plant disease management. These systems integrate machine learning (ML), deep learning (DL), computer vision, and data-driven modelling to revolutionize plant health monitoring. The primary strength of AI lies in its ability to analyze high-dimensional, heterogeneous datasets derived from imaging systems (red, green, and blue, multispectral, and hyperspectral cameras), environmental sensors, and field devices. ML and DL algorithms, such as convolutional neural networks (CNNs), support vector machines (SVMs), random forests (RF), and decision trees, process images. Furthermore, the data are used to identify subtle symptoms and classify diseases before visual symptoms become apparent. These models automate image acquisition, preprocessing, segmentation, feature extraction, and classification workflows, reducing labor costs and enabling precision disease detection at scale. Advanced image processing and segmentation facilitate accurate measurement of disease severity, such as quantifying the affected leaf area using mobile applications and field sensors (Kukadiya and Meva, 2023). By integrating site-specific weather data, crop growth models, pathogen lifecycles, and historical disease outbreaks, AI systems can forecast risks and facilitate timely, targeted interventions. Predictive analytics can recommend optimal pesticide application schedules, irrigation regimes, and fungicide choices, which can help reduce crop losses and ensure environmental sustainability. Some researchers have employed UAVs (drones) or ground robots for hyperspectral imaging of large fields, followed by automated site-specific spraying based on AI-generated disease risk maps, thus minimizing chemical inputs and reducing off-target effects (Subeesh *et al.*, 2021).

The convergence of AI and IoT aids real-time data integration from diverse sources (soil sensors, weather stations, and mobile devices), thereby enhancing decision support for farmers. AI-powered apps, such as Plantix, Plant Doctor, CropIn, and SmartFarm, allow users to upload crop images and instantly receive diagnostic reports, recommendations, and agronomic advice in several languages. These mobile solutions also incorporate weather forecasts, market analytics, and resource management tools, thereby promoting holistic, data-driven crop protection. The collaboration between Microsoft and ICRISAT, India, enabled smallholder cotton farmers to use mobile-based AI for disease alerts, which helped reduce crop losses and unnecessary chemical application. In Australia, DeepLeaf utilizes drone imagery and CNN models for wheat rust surveillance, whereas crop health monitoring innovations in Brazil and Israel employ satellite imagery and multispectral analytics for early disease identification and interventions (Minhans *et al.*, 2025).

Despite these advances, key barriers to adoption remain, including limited access to training data, technical expertise requirements, model interpretability challenges, and affordability for smallholder farmers to purchase these technologies. Addressing these barriers requires investment in farmer training, the development of inclusive and region-specific AI models, public-private collaboration, and supportive agricultural policies (John *et al.*, 2023).

Conclusion

Although once effective, conventional crop protection methods are increasingly constrained by various factors, creating an urgent need for sustainable and advanced alternatives to these methods. Emerging tools have shown strong potential to transform modern crop protection. Integrating these innovations into IPM and climate-smart agricultural strategies will be crucial as farming systems evolve. Continued investment in research, capacity building, and evidence-based policies is essential to ensure that these technologies become practical and impactful. The convergence of novel innovations provides a meaningful approach to enhance agricultural practices, ultimately strengthening food security.

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