

Modern technologies in the diagnosis and management of plant-pathogenic fungi: From CRISPR to the microbiome and Artificial Intelligence

Intesar Ali Mezeal * and Rand Haider Ali

Department of Biology, College of Science, Mustansiriyah University, Baghdad 10052, Iraq.

International Journal of Science and Research Archive, 2026, 20(01), 150–157

Publication history: Received on 26 May 2026; revised on 05 July 2026; accepted on 07 July 2026

Article DOI: <https://doi.org/10.30574/ijrsra.2026.20.1.1435>

Abstract

Plant-pathogenic fungi still constitute one of the most significant biological constraints on agricultural productivity, food safety, and sustainable agriculture. It has become increasingly challenging to mitigate their effects due to the effects of climatic variability, monoculture, plant material transport across national borders, greenhouse production, fungicide resistance, and others. While classical diagnostics based on symptoms, microscopic observations, isolations, and morphology are still vital in practice, they are often slow and expertise-reliant and fail to provide the necessary early warning. The present review article explores contemporary developments in the diagnostics and management of plant-pathogenic fungi with a particular emphasis on CRISPR-based methods of diagnostics, loop-mediated isothermal amplification (LAMP), portable diagnostics, artificial intelligence (AI), disease suppression via the manipulation of microbiomes, biological control, RNA-based protection of crops, nanotechnology, and integrated disease management. It is concluded that the contemporary management of plant-pathogenic diseases should go beyond the single-method approach. CRISPR and LAMP techniques advance pathogen detection during initial stages of infection; artificial intelligence helps with image-assisted disease diagnosis and prediction; microbiome science reveals the mechanisms underlying the suppression of pathogens by beneficial microbial communities; and biocontrol, RNA spraying, and nanotechnology are possible solutions which could minimize the over-reliance on chemicals. Nonetheless, the application of these innovations demands field testing, cost-effectiveness evaluation, biosafety assessment, and adaptation to local conditions. Plant pathogenic fungal diseases management in the future will be about using diagnostic and preventive approaches and decision support systems that can be used by scientists, extension agents, and farmers.

Keywords: Plant-Pathogenic Fungi; CRISPR-Cas; LAMP; Artificial Intelligence; Plant Microbiome

1. Introduction

Pathogenic fungi represent an important issue in plant pathology due to their broad range of effects on almost all major groups of crops, such as cereals, legumes, vegetables, fruits, ornamental crops, and forestry plants. Plant-pathogenic fungi cause various diseases, including rusts, smuts, powdery mildews, downy-like diseases caused by organisms similar to fungi, leaf spots, blights, wilts, root rots, damping off, stem cankers, and postharvest diseases. The damage caused by these pathogens extends beyond yield losses, and it includes a decrease in market value, mycotoxin contamination of agricultural products, reduced seed quality, and increased costs associated with crop protection.

It should be stressed that contemporary literature draws attention to the increasing threat posed by plant diseases for food security under changing climatic conditions and agricultural intensification (Gai and Wang, 2024). The efficiency of fungal pathogens in nature is associated with their capacity for dispersal and adaptation. Some fungal pathogens produce large numbers of spores, which are dispersed by wind, rain, irrigation water, soil movement, seeds, instruments, insects, and human commerce. Other fungal pathogens live in symbiosis with plants for several years via

* Corresponding author: Intesar Ali Mezeal; Email: Intesarali664@uomustansiriyah.edu.iq

sclerotia, chlamydospores, thick-walled mycelium, or plant residues infected by them. Moreover, fungal pathogens are very different in terms of ecology, being either biotrophs, which need live tissues of the hosts to survive, or necrotrophs, which kill host cells, as well as switch from one strategy to another depending on the infection stage and environmental conditions (Mishra et al., 2024). The traditional approach to disease management included diagnosis through observation, sanitation, resistant varieties, rotation of crops, and fungicides. All these techniques have their relevance even today, but with the increasing complexities involved in agricultural practices, more rapid and accurate diagnostic techniques need to be developed. Symptom diagnosis is particularly difficult because similar symptoms can be caused by various diseases, or sometimes abiotic stress can lead to symptoms identical to a disease. Wilting is an example of such symptoms, which can arise from fungal infections in the vascular system, root injuries, drought, salinity, or nematode infection. (Degani, 2025).

2. Why Modern Diagnosis Is Necessary

Diagnosis is the key step for effective control of any fungal diseases. When the symptoms are clearly visible in a field, the fungus might have established itself, formed its spores, or spread to nearby plants. In cases like nursery, greenhouses, seed banks, or quarantine checks, where one contaminated lot is enough to spread a disease in the region, diagnosis becomes crucial. The classical technique of isolation on culture media and microscopic identification can help confirm the diagnosis, but it can take several days to weeks. It also needs mycological expertise and will not work with slow-growing, non-culturable, hidden by secondary contamination, or low-abundance pathogens. (Yadav and Yadav, 2025).

The molecular tests have increased the precision and accuracy of diagnoses through direct detection of pathogen DNA/RNA in plant tissue, seeds, soil, irrigation water, or even air samples. Polymerase chain reaction (PCR), quantitative PCR (qPCR), DNA barcoding, sequencing, and metagenomics have facilitated differentiation among closely-related species and the description of the community of pathogens. However, laboratory-based diagnoses are not always readily available to farmers or local extension agents. Sending samples to a distant lab may take time, and delayed decisions often mean higher crop losses. This need has motivated the development of portable diagnostic devices to decrease the gap between sample collection and implementation of measures (Yadav and Yadav, 2025). Diagnosis in the modern era can also be seen in a disease management framework. A positive molecular outcome is only meaningful when it helps to take appropriate action: rejecting infected seeds, modifying irrigation methods, applying a specific fungicide, administering biological control, removing the affected plants, or improving the quarantine strategy. Therefore, the future of fungal detection is not just about improved sensitivity; it is about detection, interpretation, and action all at once. (Czembor et al., 2025).

3. CRISPR-Based Detection of Fungal Pathogens

CRISPR-Cas system technology has emerged as one of the most innovative technologies in pathogen diagnostics. In diagnosing pathogens using CRISPR-Cas, the technology is not employed for genome editing but is applied as a programmable recognition platform. Here, guide RNA targets the Cas protein to a specific nucleic acid sequence through collateral cleavage which generates either fluorescence or lateral flow. The main strength is specificity because the test can be tailored to detect specific sequences that differentiate pathogenic microorganisms from other closely-related races or species. CRISPR-Cas systems have been described in recent reviews as very flexible platforms in plant disease detection owing to their capacity to provide sensitivity, specificity, rapidity, and portability (Tian et al., 2025). The use of CRISPR diagnostics on fungi has been realized in detection of wheat fungal diseases. CRISPR-Cas12a-based assay has been created that has high sensitivity and specificity in the detection of fungi causing wheat diseases indicating the importance of this technology in quick diagnosis of important cereals (Mu et al., 2022). This is an important technology because wheat fungal diseases spread quickly and decision-making is essential in areas where rusts, blights, and seed-borne fungi compromise food security of the nation.

Recent studies also indicate that advancements have been made in developing CRISPR-Cas12a systems that are capable of detecting plant pathogens without the need for any conventional amplification in some cases. Even though such developments might involve detection of pathogens that are non-fungal in nature, they are significant in the area of fungal diagnosis as they point to the way forward in simplifying the chemistry of CRISPR for more field-based applications (Lagner et al., 2025). Although CRISPR diagnosis is a promising approach, it has certain limitations. In addition to the need for precise guide design and validated target sequences, it is necessary to take care of possible contamination and reliable extraction of nucleic acids. Contaminants, mixed infections, and degradation of nucleic acids may also be present in field samples. Also, fungal populations exhibit genetic diversity, making it necessary to test

primers and guide RNAs against pathogens in the region. Therefore, CRISPR needs to be coupled with classical mycology and sequencing. (Tian et al., 2025).

4. LAMP and Field-Forward Molecular Diagnostics

Another highly pertinent diagnosis tool is loop-mediated isothermal amplification (LAMP). As opposed to PCR, this technique does not need the repetition of temperature cycles since the nucleic acid is amplified using only one temperature. It becomes easy to use this tool in portable heat sources, colorimetric reactions, fluorescence-based tools, or lateral flow. A literature review on LAMP for fungal plant pathogens indicates that it has emerged as an important diagnostic tool owing to its speed, sensitivity, and ability to be used outside laboratory settings (Németh and Kovács, 2025). The use of LAMP becomes especially interesting for the diagnosis of seed health, greenhouse conditions, nursery certification, and rapid detection of the outbreak of disease. Compared to culture-based diagnostics, it allows obtaining results much more quickly. When combined with simpler DNA extraction and field-compatible detection, it can enable faster decision-making by farmers and extension workers. At the same time, LAMP requires proper design of primers because of the involvement of several primers targeting different parts of the same sequence. Poorly designed test can lead to nonspecific amplification. Contamination and sample quality may affect results interpretation. (Nemeth and Kovacs, 2025).

Diagnostic equipment is not limited only to LAMP or CRISPR. It also includes biosensors, lab-on-a-chip systems, readers used in conjunction with smartphones, immunostrips, microfluidic devices, and compact fluorescence systems. All these methods are currently under consideration for disease diagnosis in plants. They correspond to a real need: diagnostics should go to the field, greenhouse, seed lots, and border checkpoints. The most advanced diagnostic devices will be those that will allow for easy sample preparation, specificity at the molecular level, user-friendly output, and connection to management guidelines. (Yadav and Yadav, 2025).

5. Artificial Intelligence and Digital Disease Recognition

Artificial intelligence has grown very quickly in the field of plant disease diagnosis using machine learning, deep learning, and computer vision. Image-based diagnosis entails using visual symptoms found on leaves, stems, fruits, and canopies for classifying diseases or estimating their severity. Fungal diseases like rusts, powdery mildew, early blight, anthracnose, leaf spots, and fruit rots tend to have visual patterns that can be seen through cameras, smartphones, drones, and multispectral devices. Deep learning and computer vision have great value because they are non-destructive, quick, and can be used in large scale (Upadhyay et al., 2025).

Artificial intelligence tools can help in eliminating the subjectivity involved in disease assessment. Traditional severity scoring relies heavily on the knowledge and experience of the assessor, which varies among assessors. However, digital models can assist in classifying lesions, estimating affected leaf area, and even seeing patterns that cannot be seen through traditional assessments. Several reviews have indicated that models used in plant disease detection are becoming increasingly dependent on convolutional neural networks, vision transformers, transfer learning, attention mechanisms, and hybrid architectures (Shafay et al., 2025). Nevertheless, there are significant challenges to the development of AI in disease detection. Many AI systems are trained using controlled data sets with defined symptoms, homogeneous background, and lighting. In real life, however, there are many factors complicating image capture and analysis – overlapping leaves, poor lighting conditions, changes in symptoms, and co-infection. A review dedicated to machine learning and deep learning methods for disease detection notes that good-quality dataset, generalization capability of the model, and its validation in the field conditions are critical for proper detection (Nyawose et al., 2025).

Consequently, artificial intelligence should not substitute laboratory diagnostic methods and the expertise of specialists. It should rather function as an additional decision-making layer. The most efficient systems will integrate image analysis with climatic parameters, crop history, DNA sequencing, soil properties, water management, and expert confirmation. In case of fungal diseases, such integration becomes absolutely necessary, since similar symptoms can be caused by various pathogens or other non-biological stresses (Shafay et al., 2025).

6. AI, Soil Data, and Predictive Disease Management

However, the application of AI technology is not limited to image classification. It could also help to make predictive models based on weather conditions, soil properties, historical data about crops, pathogen surveillance, and microbiomes. For instance, predicting models are particularly useful for predicting fungal diseases as outbreaks of

fungal diseases are mostly conditioned by the combination of temperature, humidity, leaf wetness, irrigation, and host susceptibility (Pace et al., 2025).

Another area where AI can be helpful is soil microbiome analysis. Soil microbes produce big and complex datasets through sequencing, metabolomics, and functional analysis of soil microorganisms. Machine learning algorithms may be used for identifying microbial markers of soil health and its disease-suppressive capacity. Recently, there was a review of AI in soil microbiome analysis, which concluded that AI technologies might be used for prediction and improvement of soil health (Pace et al., 2025). For practical application of these methods to disease management, predictive models may help decision-making processes involving planting dates, cultivars, irrigation schedules, biological treatment, or fungicide application. Nevertheless, models need to be regionally calibrated since risks of infection are different in different regions. The model, which is applicable to one type of soil or climate, may not function properly in another. Thus, AI should be used for fungal disease management based on local data and cooperation between plant pathologists, data scientists, extension agents, and farmers. (Czembor et al., 2025).

7. The Plant Microbiome and Disease-Suppressive Soils

It is now understood that plant microbiome is an essential part of plant health. This community comprises microorganisms which are found within roots, shoots, leaves, seeds, internal plant tissues, and the surrounding soil. Microbiome influences nutrition, immunity, stress resistance, and pathogen resistance. The modern approach to managing plant diseases is that disease outcomes depend not only on the pathogen and host but also on the microbial community around them. (Du et al., 2025). Resistance to plant diseases provided by microbiome works through different mechanisms. Beneficial microorganisms can compete for nutrients and infection sites with pathogens, synthesize antifungal compounds, break down pathogen structures, stimulate systemic resistance, or modify root exudates. Recent review states that there is evidence that plants can recruit beneficial microorganisms, and those can provide plants with resistance to diseases. (Du et al., 2025).

The suppression of disease in soils is one of the best examples of microbiome-based disease resistance. In such soils, disease is still low even if there is a pathogen, a susceptible host, and appropriate conditions for development of disease. Suppression can be either general, caused by high microbial activity and competition between microorganisms, or specific due to antagonistic microorganisms. It follows, then, that soil health management can be one practical way of decreasing the spread of fungi-related diseases. Organic materials, composting, cover crops, minimal tillage, crop rotation, appropriate fertilizer usage, and proper irrigation practices can foster the growth of useful microorganisms. In the recently published article reviewing the issue of disease suppression in plants, it has been noted that the soil conditions and microbial activities play a pivotal role in both soil and plant health management (Priyadarshini et al., 2025).

8. Biological Control and Trichoderma-Based Management

Biological control still stands as one of the most researched alternatives to fungicide dependency. Biological control makes use of helpful microorganisms and their products that help in suppressing pathogens, inducing plant defense reactions, and promoting plant growth. In case of fungi, *Trichoderma* stands out as one of the most effective since it utilizes several mechanisms of action. This mechanism involves competition for habitat and nutrition, production of lytic enzymes and antifungal secondary metabolites, root colonization and induction of plant resistance reaction. (Yao et al., 2023). Modern literature presents the concept that *Trichoderma* is a multifunctional genus with biological control and plant growth promotion functions. This is important since an efficient biological control agent should not only inhibit the pathogen but also ensure good plant condition in the field conditions. Previous literature further indicates the involvement of *Trichoderma* in the biological control of fungi and nematode disease. (Yao et al., 2023). Mycoparasitism is another key mechanism employed by *Trichoderma* in fighting fungal pathogens. Mycoparasitism entails recognition by *Trichoderma* of pathogen hyphae, coiling and penetration of hyphae, and degradation of pathogen cell walls through the use of enzymes and metabolites. There is a review on mycoparasitism by *Trichoderma* that identifies this technique as an effective tool for combating soil-borne plant pathogens (Singh et al., 2024). This is especially relevant for plant diseases caused by *Rhizoctonia*, *Sclerotium*, *Fusarium*, and other stubborn soil-borne fungi.

Nonetheless, biological control is not reliable in all conditions in the field. The efficacy of microbial inoculants depends on the quality of strains used, formulation of inoculant, storage conditions, soil temperature, moisture, pH, organic matter, presence of indigenous microbiota, plant species, pathogens' abundance, and compatibility with chemicals used in fungicides. Therefore, biocontrol has to be combined with diagnosis, sanitation, crop rotation, resistant varieties, and

other soil health management approaches. In this regard, innovative biocontrol research is making use of meta-omics, next generation sequencing and microbiome engineering (Gómez-Lama Cabanás and Mercado-Blanco, 2025).

9. RNA-Based Protection and Spray-Induced Gene Silencing

The RNA-mediated method of protecting plants from disease-causing pathogens relies on the principle of sequence-specific suppression of pathogen genes. The process of spray-induced gene silencing involves application of the double-stranded RNA or small RNA to the exterior of the plant. The RNAs used in the technique are aimed at suppressing expression of some essential or virulence-associated genes in the pathogen leading to a decrease in infection or fungal growth. The RNA-mediated control can prove to be a more efficient method compared to other pesticides as it might be more targeted. (Mann et al., 2023). In their review of RNA-based control of fungal pathogens in plants, authors describe it as an environmentally-friendly alternative to chemical-based pest control methods (Mann et al., 2023). The process of spray-induced gene silencing is particularly useful as it does not involve modification of the plant genome.

Recent research demonstrates the emergence of spray-induced gene silencing as an important focus in the protection of crops. Recent review outlines the fundamentals, progress, and trends in SIGS, mentioning that sprayable dsRNAs technologies are approaching the implementation in crop protection (Chen et al., 2025). Other comprehensive guidelines provide information on designing and evaluation of SIGS for plant-pathogenic fungi, highlighting the importance of target identification, dsRNA construction and delivery (Mosquera et al., 2025). The key limitations of the RNA-based approach include RNA instability, cost, efficiency of delivery, environmental persistence, RNA uptake into fungal cells, and regulation. Nanocarriers may help to address these limitations. Artificial nanovesicles were proved to be able to enhance dsRNA delivery in spray-induced gene silencing systems, thus showing how RNA technology and nanotechnology could be integrated into crop protection (Qiao et al., 2023).

10. Nanotechnology in Fungal Disease Management

Nanotechnology provides further options for treatment of fungi-associated diseases. The nanomaterials could be utilized as fungicidal, transporters of fungicides, transporters of RNA molecules, or sensors for the detection of pathogens. Metal nanoparticles, metal oxides, polymeric nanoparticles, nanoemulsions, and silica-based transporters were reported for their potential use in improving stability, controlled release, adhesion to plants, penetration, and dosage efficacy. (Ogwu and Izah, 2025). The benefit of using nanotechnology is that it would be possible to decrease the required quantity of an active substance and increase the delivery of it to the point of action. According to one recent review, nanotechnology-based inventions could play a role in controlling fungal pathogens in plants and connect the health of plants to the sustainability of the environment (Ogwu and Izah, 2025). But then again, nanotechnology should be analyzed cautiously. This is because nanoparticles can impact friendly microbes, build up in the soil, cause phytotoxicity, or even cause food safety issues. The performance of the nanoparticles will depend on their size, coating, concentration, soil composition, crops, and environmental factors. As such, the use of nanotechnology in managing diseases should not be taken just because it's technically sound. (Ogwu and Izah, 2025).

11. CRISPR Genome Editing and Host Resistance

CRISPR tools help to manage diseases with genome editing. In comparison with CRISPR-based diagnostics, genome editing changes the genetic makeup of the plant. Genome editing might be useful to knock out the genes of susceptibility or to enhance the immune response or speed up the breeding process with resistance. Genome editing could be especially helpful for managing diseases caused by fungi when breeding is slow or resistance is polygenic. (Das et al., 2023). Genome editing is considered a prospective technology in plant disease management, including fungi, due to the capability to modify the genes related to susceptibility and resistance (Das et al., 2023). Nevertheless, durable resistance is achieved not only by modifying one gene. Fungi evolve, and resistance mechanisms could become useless because of emergence of races and virulent forms of a fungus. Therefore, genome editing should be combined with breeding, monitoring of pathogens, and various agricultural practices. Genome-edited crops require proper regulation and public reception, which differ from country to country. The use of genome editing in breeding influences commercialization. In case of scientific review articles, it is necessary to consider CRISPR breeding technology as prospective but context-dependent. (Das et al., 2023).

12. Integrated Management and Reduced Chemical Dependence

Management of fungal diseases in modern times should take an integrated approach and not just depend on any technological aspect. None of the diagnostic methods, biocontrol agents, artificial intelligence systems, RNA sprays, or fungicides can solve the problem of all fungal diseases by themselves. The approach of integrated disease management includes resistant varieties, good seedlings, sanitation, crop rotation, proper irrigation techniques, nutrient management, good canopy structure, improved soil health, biological control, and proper use of fungicides. (Adkar-Purushothama et al., 2025).

Use of non-chemical methods is increasing due to concerns about the environment, fungicide resistance, and sustainable agriculture needs. One review of non-chemical methods for controlling fungal pathogens has included cultural methods, biological methods, natural products from plants, RNA-based technologies, nanotechnology, and microbiome engineering. (Adkar-Purushothama et al., 2025) The comprehensive approach is essential because it does not substitute one over-used technique for another technique. Management of field crops also involves decision support and cultivar selection. A review on management of fungi causing diseases in field crops highlights the use of integrated pest management, agroecology, resistance cultivars, climate-resilient decisions, and advisory services that may help in reducing economic and environmental impacts due to fungi (Czembor et al., 2025). Similarly, monitoring and management are of great importance for horticultural crops that face a high risk of disease development and market quality standards (Wang et al., 2025).

13. Limitations and Implementation Challenges

While promising, application of these modern technologies is hindered by various obstacles. First, cost and infrastructure may prove a barrier in adoption of such tools. CRISPR, sequencing, AI platforms and nanotechnology may require some equipment, expertise, chemicals, data storage or interpretation. Second, the technique should be validated in the field setting. The test that works perfectly in the lab environment does not necessarily work well on the farm where variability is present. Third, pathogens' genotypic diversity might influence the performance of the assay, as it may be based on limited genomic information.

Fourth, technology should help to make a decision. It needs to tell farmers what to do – to water differently, to destroy infected plants, to apply biocontrol, fungicides, change cultivars, or not plant crops susceptible to a particular disease at all. Finally, biosafety must be considered for sustainable application. This concerns RNA-based products, nanoparticles, microbial inoculants and genome-edited cultivars. Lastly, extension and education are very important. New technologies will not be useful if they are restricted to laboratory settings only. Training should be done in such a way that it allows extension agents and farmers to understand the process of sampling, diagnosis, disease risks, and integration of management. Technologies that will be most relevant in resource-poor areas include those that are reliable and economical.

14. Future Perspectives

Management of plant pathogenic fungal diseases in the future will require the use of integrated platforms. An example of an operational system in the future may involve field observations coupled with automated symptom detection through AI technology followed by portable molecular detection using LAMP or CRISPR. Weather conditions and soil data will estimate the risk of disease occurrence, while microbiome signatures will detect the suppressiveness or conduciveness of the soil. Based on the risk levels and the pathogens involved, biocontrol products, cultural control measures, RNA sprays, low-risk fungicides, or resistant varieties will be used. Priority areas of research will include affordable diagnostic techniques, regional pathogen databases, open image data sets, locally adaptive biocontrol products, field-applicable RNA spray preparations, safe nanocarriers, and microbiome signatures of soil suppressiveness. These priority research areas become particularly relevant in arid and semi-arid agriculture where heat stress, soil salinity, irrigation, and protected cropping can affect disease dynamics. The key finding from this review is that modern technological tools become highly useful if they become integrated and locally adaptive.

15. Conclusion

Despite being a significant problem for agriculture, plant pathogenic fungi have been revolutionized in terms of diagnosis and management by modern-day technology. CRISPR-based assays and LAMP have facilitated faster detection; portable diagnostic systems allow on-site testing; artificial intelligence helps with image-based detection and prediction modeling; microbiome research sheds light on the ecological basis of disease suppression; and biological

control, RNA-based protection, nanotechnology, and gene editing offer novel approaches for managing the problem. However, the future will not be a conflict between the old and the new. Rather, efficient fungal disease management will entail integration of classical plant pathology, molecular-level precision, ecological knowledge, intelligent systems, and agronomically sound practice. The most promising systems will be those able to detect pathogens in early stages, correctly assess the risk of disease, enhance plant and soil health, minimize unnecessary reliance on chemicals, and maintain agricultural relevance.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

- [1] Adkar-Purushothama, C. R., Chettimada, A., and Murali, M. (2025). Non-chemical control of fungal pathogens in crops: a one-health perspective on strategies, mechanisms and future directions. *Frontiers in Plant Science*, 16, 1746521. <https://doi.org/10.3389/fpls.2025.1746521>
- [2] Chen, C., Imran, M., Feng, X., Shen, X., and Sun, Z. (2025). Spray-induced gene silencing for crop protection: recent advances and emerging trends. *Frontiers in Plant Science*, 16, 1527944. <https://doi.org/10.3389/fpls.2025.1527944>
- [3] Chen, X., Luo, Y., Li, F., et al. (2025). Trichoderma: dual roles in biocontrol and plant growth promotion. *Microorganisms*, 13(8), 1840. <https://doi.org/10.3390/microorganisms13081840>
- [4] Czembor, E., Tratwal, A., Pukacki, J., Krystek, M., and Czembor, J. H. (2025). Managing fungal pathogens of field crops in sustainable agriculture and AgroVariety internet application as a case study. *Journal of Plant Protection Research*, 65(1), 1-26.
- [5] Das, K., Ayim, B. Y., Borodynko-Filas, N., Das, S. C., and Aminuzzaman, F. M. (2023). Genome editing CRISPR/Cas9 in plant disease management: challenges and future prospects. *Journal of Plant Protection Research*, 63(2), 159-172. <https://doi.org/10.24425/jppr.2023.145761>
- [6] Degani, O. (2025). Plant fungal diseases and crop protection. *Journal of Fungi*, 11(4), 274. <https://doi.org/10.3390/jof11040274>
- [7] Du, Y., Han, X., and Tsuda, K. (2025). Microbiome-mediated plant disease resistance: recent advances and future directions. *Journal of General Plant Pathology*, 91, 1-17. <https://doi.org/10.1007/s10327-024-01204-1>
- [8] Gai, Y., and Wang, H. (2024). Plant disease: a growing threat to global food security. *Agronomy*, 14(8), 1615. <https://doi.org/10.3390/agronomy14081615>
- [9] Gomez-Lama Cabanas, C., and Mercado-Blanco, J. (2025). Groundbreaking technologies and the biocontrol of fungal vascular plant pathogens. *Journal of Fungi*, 11(1), 77. <https://doi.org/10.3390/jof11010077>
- [10] Lagner, J. R., Newberry, E. A., Rivera, Y., Zhang, L., Vakulskas, C. A., and Qi, Y. (2025). Amplification-free detection of plant pathogens by improved CRISPR-Cas12a systems: a case study on phytoplasma. *Frontiers in Plant Science*, 16, 1544513. <https://doi.org/10.3389/fpls.2025.1544513>
- [11] Mann, C. W. G., Sawyer, A., Gardiner, D. M., Mitter, N., Carroll, B. J., and Eamens, A. L. (2023). RNA-based control of fungal pathogens in plants. *International Journal of Molecular Sciences*, 24(15), 12391. <https://doi.org/10.3390/ijms241512391>
- [12] Mishra, S., Srivastava, A., Singh, A., Pandey, G. C., and Srivastava, G. (2024). An overview of symbiotic and pathogenic interactions at the fungi-plant interface under environmental constraints. *Frontiers in Fungal Biology*, 5, 1363460. <https://doi.org/10.3389/ffunb.2024.1363460>
- [13] Mosquera, S., Ginesy, M., Bocos-Asenjo, I. T., Amin, H., Diez-Hernando, S., Diez, J. J., and Nino-Sanchez, J. (2025). Spray-induced gene silencing to control plant pathogenic fungi: a step-by-step guide. *Journal of Integrative Plant Biology*, 67(3), 801-825. <https://doi.org/10.1111/jipb.13848>
- [14] Mu, K., Ren, X., Yang, H., Zhang, T., Yan, W., Yuan, F., Wu, J., Kang, Z., Han, D., Deng, R., and Zeng, H. (2022). CRISPR-Cas12a-based diagnostics of wheat fungal diseases. *Journal of Agricultural and Food Chemistry*, 70(23), 7240-7247. <https://doi.org/10.1021/acs.jafc.1c08391>

- [15] Nemeth, M. Z., and Kovacs, G. M. (2025). A comprehensive guide to loop-mediated isothermal amplification, an emerging diagnostic tool for plant pathogenic fungi. *Frontiers in Plant Science*, 16, 1568657. <https://doi.org/10.3389/fpls.2025.1568657>
- [16] Nyawose, T., Maswanganyi, R. C., and Khumalo, P. (2025). A review on the detection of plant disease using machine learning and deep learning approaches. *Journal of Imaging*, 11(10), 326. <https://doi.org/10.3390/jimaging11100326>
- [17] Ogwu, M. C., and Izah, S. C. (2025). Nanotechnology for fungal pathogen control in crops. *Frontiers in Fungal Biology*, 6, 1653214. <https://doi.org/10.3389/ffunb.2025.1653214>
- [18] Pace, R., Schiano Di Cola, V., Monti, M. M., Affinito, A., Cuomo, S., Loreto, F., and Ruocco, M. (2025). Artificial intelligence in soil microbiome analysis: a potential application in predicting and enhancing soil health-a review. *Discover Applied Sciences*, 7, 85. <https://doi.org/10.1007/s42452-024-06381-4>
- [19] Priyadarshini, C., Lal, R., Yuan, P., Liu, W., Adhikari, A., Bhandari, S., and Xia, Y. (2025). Plant disease suppressiveness enhancement via soil health management. *Biology*, 14(8), 924. <https://doi.org/10.3390/biology14080924>
- [20] Qiao, L., Nino-Sanchez, J., Hamby, R., Capriotti, L., Chen, A., Mezzetti, B., and Jin, H. (2023). Artificial nanovesicles for dsRNA delivery in spray-induced gene silencing for crop protection. *Plant Biotechnology Journal*, 21(4), 854-865. <https://doi.org/10.1111/pbi.14001>
- [21] Shafay, M., Hassan, T., Owais, M., Hussain, I., Khawaja, S. G., Seneviratne, L., and Werghi, N. (2025). Recent advances in plant disease detection: challenges and opportunities. *Plant Methods*, 21, 140. <https://doi.org/10.1186/s13007-025-01450-0>
- [22] Singh, S., Singh, A. K., Pradhan, B., Tripathi, S., Kumar, K. S., Chand, S., Rout, P. R., and Shahid, M. K. (2024). Harnessing Trichoderma mycoparasitism as a tool in the management of soil dwelling plant pathogens. *Microbial Ecology*, 87, 158. <https://doi.org/10.1007/s00248-024-02472-2>
- [23] Spooren, J., van Bentum, S., Thomashow, L. S., Pieterse, C. M. J., Weller, D. M., and Berendsen, R. L. (2024). Plant-driven assembly of disease-suppressive soil microbiomes. *Annual Review of Phytopathology*, 62, 1-30. <https://doi.org/10.1146/annurev-phyto-021622-100127>
- [24] Tian, Y., Li, C., and Zhao, E. (2025). Recent advances in the detection of plant diseases based on the CRISPR-Cas system. *Analytical Chemistry*. <https://doi.org/10.1021/acs.analchem.5c07871>
- [25] Upadhyay, A., Chandel, N. S., Singh, K. P., Chakraborty, S. K., Nandede, B. M., Kumar, M., Subeesh, A., Upendar, K., Salem, A., and Elbeltagi, A. (2025). Deep learning and computer vision in plant disease detection: a comprehensive review of techniques, models, and trends in precision agriculture. *Artificial Intelligence Review*, 58, 92. <https://doi.org/10.1007/s10462-024-11100-x>
- [26] Wang, Q., Li, H., Zhang, Y., Liu, J., et al. (2025). Fungi in horticultural crops: promotion, pathogenicity and monitoring. *Agronomy*, 15(7), 1699. <https://doi.org/10.3390/agronomy15071699>
- [27] Yadav, A., and Yadav, K. (2025). Portable solutions for plant pathogen diagnostics: development, usage, and future potential. *Frontiers in Microbiology*, 16, 1516723. <https://doi.org/10.3389/fmicb.2025.1516723>
- [28] Yao, X., Guo, H., Zhang, K., Zhao, M., Ruan, J., and Chen, J. (2023). Trichoderma and its role in biological control of plant fungal and nematode disease. *Frontiers in Microbiology*, 14, 1160551. <https://doi.org/10.3389/fmicb.2023.1160551>
- [29] Zhou, J., Zhang, X., Qu, Z., Zhang, C., Wang, F., Gao, T., Yao, Y., and Liang, J. (2024). Progress in research on prevention and control of crop fungal diseases in the context of climate change. *Agriculture*, 14(7), 1108. <https://doi.org/10.3390/agriculture14071108>
- [30] Phurbu, D., et al. (2025). Rapid and sensitive diagnosis of plant quarantine fungi *Alternaria tritricina* and *Plenodomus libanotidis* based on the RPA-CRISPR/Cas12a system. *IMA Fungus*.