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AI-Assisted Early Detection of Plant Diseases under Field Conditions

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Plant diseases are a major limitation with regard to both crop productivity and sustainable agricultural production. Traditional methods of diagnosing diseases generally rely on visual symptoms and the judgement of experts, a process which can be time-consuming and hard to carry out over large areas of agriculture. More seriously, visible symptoms do not always appear until considerable development of the pathogen has taken place, thus decreasing the chances of timely disease control. Artificial intelligence (AI), especially machine learning and deep learning, has become a promising means for quickly and automatically detecting plant diseases. Recent progress in convolutional neural networks, object-detection models, Vision Transformers, hyperspectral and multispectral imaging, thermal sensing, unmanned aerial vehicles, and the integration of multimodal data has extended the potential of AI from simple disease recognition to early and field-scale disease diagnosis. Nevertheless, models trained on images taken in controlled laboratory conditions often perform poorly in natural field conditions due to variations in illumination, background, cultivar, growth stage, disease severity, and environmental stresses. Combining plant images with information on the environment and plant physiology may enhance the reliability of early disease detection and disease-risk prediction. Explainable artificial intelligence can also help improve the interpretation of and acceptance for AI-based diagnosis. The article looks at the most recent advances, applications, challenges, and future possibilities of using AI to detect plant diseases in the field, with a special focus on real-world validation, multimodal sensing, pre-symptomatic detection, and precise disease management.

Keywords: Artificial intelligence, plant disease detection, early diagnosis, deep learning, field conditions, hyperspectral imaging, multimodal sensing, precision agriculture

Introduction

Plant diseases are a problem for farmers because they can hurt the amount of food we get from crops the quality of the food and the money farmers make. To deal with plant diseases we need to find out what is wrong with the plants quickly and correctly. Usually, people look at the plants to see what is wrong like spots on the leaves. leaves turning yellow or leaves dying. Then they do more tests if they need to. This way of figuring out what is wrong with plants is still very important but it can take a lot of time it is work and we need experts to do it. Also we can only see what is wrong with the plants when the disease has already gotten bad. So we need ways to find out if plants are sick before it is too late and this is important for growing food in a way that is good for the Earth. Computers are now being used to help figure out what is wrong with plants. They can look at a lot of pictures and information from sensors. Find patterns that mean the plants are sick. In the few years people have been studying ways to use computers to find plant diseases, like special kinds of computer programs called convolutional neural networks and other techniques.. Now people are trying to use these computer programs to find diseases when they are just starting and when the plants are growing outside in fields. This is a change because fields are much more complicated, than laboratories and plant diseases can be harder to find when plants are growing outside.

AI-Based Plant Disease Detection

Early AI-based plant disease detection systems generally relied on machine-learning algorithms that used manually selected features such as colour, texture, shape, and lesion characteristics. Algorithms including Support Vector Machines, Random Forest, and other classifiers were used to differentiate healthy and diseased plants. The development of deep learning significantly changed this approach because deep-learning models can automatically learn disease-related features directly from images. CNNs have become one of the most widely used deep-learning approaches for plant disease recognition. They can learn features such as lesion patterns, colour changes, leaf texture, chlorosis, and necrotic regions from plant images. More advanced architectures, including Res Net, Dense Net and Efficient Net, have improved feature extraction and classification performance. Object-detection models such as YOLO can additionally identify the location of diseased regions, while segmentation approaches can separate diseased tissue from healthy plant tissue. These capabilities are particularly useful for field applications because plants may appear at different positions, scales, and orientations within an image. Recent research has also introduced Vision Transformers (ViTs) and hybrid CNN–Transformer models for plant disease detection. These models can learn relationships between different regions of an image and have become an important alternative to conventional CNN-based systems. However, the success of these models in controlled datasets does not necessarily guarantee successful application in real agricultural fields.

Early and Pre-Symptomatic Disease Detection

The major advantage of AI-assisted early detection is the possibility of identifying disease before severe symptoms become visible. Pathogen infection can produce physiological and biochemical changes within a plant before obvious symptoms appear on the leaves. These changes may affect chlorophyll content, water status, photosynthetic activity, cellular structure, reflectance characteristics, and leaf temperature. Advanced imaging technologies can potentially detect these subtle changes. For example, hyperspectral imaging records reflectance information across numerous narrow wavelength bands and may identify changes associated with pathogen infection that are not easily visible in ordinary RGB images. Multispectral imaging similarly provides information from selected spectral regions, while thermal imaging can detect changes in leaf or canopy temperature associated with altered plant water relations and physiological stress. The combination of these sensing technologies with AI can therefore provide a pathway from pathogen infection to physiological change, sensor detection, AI analysis, and early disease diagnosis. This approach is particularly promising because it could provide additional time for disease management before disease symptoms become severe.

AI under Real Field Conditions

Plant disease detection is a problem because of the difference between pictures taken in a lab and pictures taken in a field. In a lab people usually take pictures of leaves against a background with good light and the symptoms are easy to see. But when you take pictures in a field it is a lot harder because the background is messy there is soil and weeds and shadows and the sunlight is not always good. There are also insects and dust and plants that're not all the same age. Plant disease detection is also tricky because the symptoms can look different depending on the type of plant the weather, the kind of disease how long the plant has been sick and how sick the plant is. Sometimes the symptoms of a disease can look like the symptoms of something like when a plant is too dry or does not have enough food or when it has been hurt by a weed killer. All these things can make it hard for a computer to correctly identify plant diseases when it is shown pictures, from a field.

So when we are trying to teach a computer to detect plant diseases we need to use a lot of pictures from fields not just from labs. We need pictures from places, different times of year different kinds of plants and different stages of growth. We also need to test the computer in a field to make sure it can correctly identify plant diseases in a real world setting, not in the pictures it was trained on. This is called field validation and it is very important to make sure the computer is working correctly.

Multimodal AI for Disease Prediction

A major recent direction is the integration of multiple types of information rather than relying only on plant photographs. Disease development is influenced by environmental conditions such as temperature, relative humidity, rainfall, leaf wetness, soil moisture, and crop growth stage. Combining these variables with plant images can potentially improve disease prediction. For example, a multimodal system could integrate RGB images, temperature, relative humidity, rainfall, soil moisture, and crop growth stage and use these data to estimate disease probability and severity. Such systems can move plant disease detection from simple image classification toward disease-risk prediction. This approach is particularly relevant to plant pathology because disease development is closely related to interactions among the host, pathogen, and environment. Thus, integrating AI with environmental and epidemiological information may provide a more biologically meaningful approach to disease forecasting and precision crop protection.

Explainable Artificial Intelligence

Although AI models can provide highly accurate predictions, their decision-making processes may be difficult to understand. This is an important limitation when AI is used for scientific diagnosis and agricultural decision-making. Explainable artificial intelligence (XAI) can help identify which features or regions of an image contributed to a model's prediction. Techniques such as Grad-CAM, SHAP, LIME, and attention maps can highlight important regions of a plant image. For example, if an AI model identifies a fungal disease, an explanation map should ideally indicate the lesion or symptom region rather than unrelated background features. Such approaches can increase confidence in AI predictions and allow plant pathologists to compare AI-generated evidence with known disease symptoms. Therefore, future field-based disease detection systems should aim not only for high accuracy but also for biological interpretability and explainability.

Major Challenges and Research Gaps

Despite rapid developments, several challenges limit the practical application of AI in plant disease diagnosis. The first is the limited availability of large, accurately labelled field datasets. Collecting field images with reliable disease identification and severity information requires considerable time and expertise. The second challenge is generalization. A model trained using images from one location or cultivar may not perform equally well in another location, season, or cultivar. Another important challenge is distinguishing pathogen-induced symptoms from abiotic stress. Yellowing, wilting, and leaf necrosis may result from several different causes, and an AI model trained only on disease images may produce incorrect diagnoses. Pre-symptomatic detection is also technically challenging because physiological changes occurring before visible symptoms can be subtle. Computational requirements are another limitation. Large deep-learning models may require substantial processing power, whereas practical field applications may require lightweight models capable of running on smartphones, drones, or edge devices. Finally, many studies still require stronger independent field validation to demonstrate that AI models can operate reliably under diverse agricultural conditions.

Future Perspectives

The future of AI-assisted plant disease detection is likely to move beyond simple image classification toward integrated, predictive and field-deployable systems. Multimodal AI combining images, spectral information, thermal data, and environmental variables could improve early disease detection and disease-risk prediction. UAVs and other remote-sensing platforms may enable monitoring of large agricultural areas, while smartphone-based and edge-AI systems could make disease diagnosis more accessible at the farm level. Another important direction is the development of explainable and lightweight AI models. Such systems should provide not only a disease prediction but also information about the affected area, disease severity, confidence level, and factors contributing to the prediction. Integration of AI with plant disease epidemiology could eventually allow continuous crop monitoring and early warning systems. The ultimate objective should therefore be to develop systems capable of moving from detection after visible symptoms to early or pre-symptomatic diagnosis and disease-risk forecasting. Such systems could support timely and targeted disease management, reduce unnecessary pesticide applications, and contribute to more sustainable crop production.

Conclusion

AI-assisted early detection represents an important emerging direction in plant pathology. Deep learning, computer vision, hyperspectral and multispectral imaging, thermal sensing, UAVs, and multimodal data analysis are providing new opportunities for rapid and automated disease diagnosis. However, the major challenge is to translate high performance obtained from controlled datasets into reliable performance under real agricultural field conditions. Future research should therefore prioritize diverse field datasets, independent validation, pre-symptomatic detection, integration of environmental information, explainable AI, and lightweight models suitable for field deployment. The combination of AI with plant pathology and disease epidemiology has the potential to transform disease management from reactive treatment after symptom development to proactive and precision-based disease prevention.