How Artificial Intelligence Can Support Modern Horticulture?

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Abstract

Modern horticulture faces increasing challenges related to the rising demand for high-quality crops, limited environmental resources, and the need for improved production efficiency. Artificial intelligence (AI), encompassing machine learning, deep learning, and advanced analysis of sensor and image data, offers significant potential to support decision-making and automation in plant cultivation systems. The aim of this manuscript is to examine current and emerging applications of AI in horticulture, with particular emphasis on disease and stress detection, microclimate control in controlled-environment agriculture, robotic harvesting, and the enhancement of breeding programs. A review of scientific literature and industrial deployment cases demonstrates that AI can contribute to improved precision of cultivation practices, reduction of production losses, and more sustainable resource management. However, several challenges remain, including data standardization, model interpretability, and the economic feasibility of implementation. The findings highlight that further development of AI applications in horticulture requires close collaboration between researchers, practitioners, and technology providers, as well as progress in digital infrastructure and agronomic competence-building.

Keywords: Artificial Intelligence; Convolutional Neural Networks; Recurrent Neural Networks; Classification Algorithms

Introduction

Contemporary horticulture faces dynamic transformations driven by the growing demand for sustainable plant production, resource-use optimization, and adaptation to changing environmental conditions [1]. Ongoing climate change, pressure to reduce emissions and water consumption, soil degradation, and the need to minimize chemical inputs pose challenges that demand the adoption of technologies characterized by high precision and efficiency [2]. In this context, artificial intelligence (AI)-understood as a set of methods encompassing machine learning, deep learning [3], image analysis, and optimization algorithms-emerges as a key component of modern decision-support systems in horticulture (Table 1). In recent years, the scientific literature has reported a marked increase in research addressing AI applications in greenhouse cultivation [4], plantation monitoring, plant phenotyping, and the automation of agrotechnical operations. Empirical and review studies demonstrate that deep learning techniques enable high-precision recognition of disease symptoms and biotic stress based on leaf images or overall plant morphology [3], thereby allowing early intervention and yield loss reduction. Simultaneously, AI-driven environmental control systems employing predictive models contribute to significant energy savings and optimization of climatic conditions in greenhouses and controlled-environment production facilities [5,6].

Another major area of development involves the integration of advanced sensors, remote sensing technologies (both satellite and unmanned), and robotics with machine learning algorithms to enable precision phenotyping and automated monitoring [7]. These solutions facilitate the acquisition of multidimensional morphological, physiological, and biochemical data across temporal scales, accelerating varietal selection, resistance assessment, and crop protection planning (Table 1). The literature also documents the growing use of autonomous ground and aerial platforms that complement traditional data sources by providing high-resolution information suitable for AI-based analysis [8]. Translational research increasingly employs multi-omics approaches combined with AI algorithms, enabling the identification of genetic and metabolic markers relevant to

agronomic traits and the optimization of breeding programs [9]. The application of machine learning to large biological datasets supports decision-making processes in breeding and production, opening new prospects for more targeted and resilient agriculture (Figure 1, Table 1). Despite promising outcomes, the literature highlights several limitations and challenges hindering the full integration of AI into horticultural practice.

Key barriers include the lack of standardization and interoperability of data from diverse sensors [7] and platforms, limited availability of representative and anonymized training datasets, issues with the interpretability of deep learning models [3], and the high cost of implementation alongside the need to enhance user competencies. Furthermore, successful deployment must also consider ethical and regulatory aspects related to data privacy and accountability for decisions made by autonomous systems [10]. The objective of this publication is to present the current state of knowledge regarding the applications of artificial intelligence in modern horticulture, with an emphasis on empirical evidence from recent studies and the identification of areas requiring further research. Specifically, the text will discuss: (i) technologies and algorithms used in plant diagnostics and monitoring; (ii) control and optimization systems in greenhouse and controlled-environment cultivation; (iii) the role of sensors and autonomous platforms in phenotyping; (iv) AI applications in breeding and integrated pest management; and (v) the economic and ethical implications of implementation. This literature review aims not only to synthesize existing achievements but also to identify research gaps and provide practical recommendations for the adaptation of AI in sustainable horticulture.

Research Methods

This publication employs an analytical and comparative review approach, integrating systematic scientific literature databases with technical reports and implementation documentation of selected artificial intelligence-assisted systems. In the first stage, literature searches were conducted using Scopus, Web of Science, and Google Scholar databases, applying keywords such as "artificial intelligence in horticulture," "controlled environment agriculture," "plant disease detection deep learning," "crop phenotyping sensors," and "multi-omics plant breeding." The collected publications were analyzed with respect to research scope, applied methodologies, types of input data, and performance evaluation metrics of the models (Figure 1).

Subsequently, machine learning, deep learning, and hybrid systems (combining visual, environmental, and genetic data) used in diagnostics, phenotyping, and automation of horticultural practices were compared. The analysis focused primarily on convolutional neural networks (CNN), recurrent neural networks (RNN), classification algorithms (SVM, Random Forest), as well as predictive model-based systems employed for greenhouse microclimate control (Table 1). Additionally, implementation reports from commercial farms and research centers were analyzed to assess the practical deployment of AI-based systems [11]. This enabled comparison between experimental results and actual performance outcomes under production conditions, taking into account factors such as the economic costs of system integration, hardware requirements, and the level of operator expertise [12].
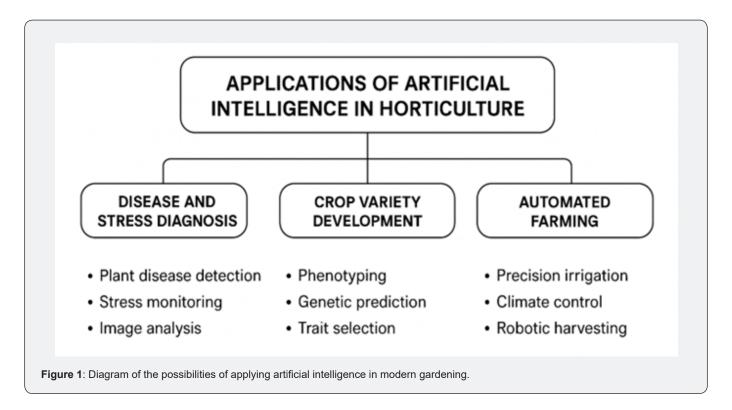
Table 1: Potential Applications of Artificial Intelligence in Modern Horticulture.

Application Area	AI Techniques Used	Example Outcomes	Limitations / Challenges
Disease and Stress Diagnosis	Convolutional Neural Networks (CNN), Image Recognition	Early detection of fungal and bacterial diseases	Requires highquality labeled image datasets
Crop Variety Development	Multiomics data integration, Predictive modeling	Faster selection of resilient genotypes	Computational complexity and data harmonization issues
Automated Farming	Robotics, Machine Vision, Reinforcement Learning	Automated harvesting and targeted weeding	Precision and speed still lower than skilled human labor
Climate and Resource Control	Machine Learning predictive models	Optimized energy, water, and CO_2 usage	Requires dense sensor networks and continuous calibration

Review of Artificial Intelligence Applications in Horticulture

Applications of artificial intelligence (AI) in horticulture encompass a broad spectrum of processes ranging from plant condition monitoring and disease diagnosis to the automation of cultivation practices and optimization of growth environments. In recent years, there has been a rapid expansion of systems based on machine learning and deep learning [3], designed to support real-time decision-making in production management (Figure 1). One of the most prominent areas of application is remote monitoring of plant health through image analysis [8]. Convolutional neural network (CNN) algorithms enable the identification of diseases, pests, and nutrient deficiencies based on images of leaves, stems, and fruits (Figure 1). These systems are deployed in both greenhouse and open-field crops, often in conjunction with mobile devices or cameras mounted on unmanned aerial vehicles (drones) [4]. Another important category of applications involves microclimate control systems for controlled-environment cultivation [13]. In greenhouses, vertical farms, and hydroponic systems, predictive algorithms analyze data from sensors measuring temperature, humidity, light intensity, and CO_2 concentration to automatically adjust environmental parameters [14].

Figure 1: Diagram of the possibilities of applying artificial intelligence in modern gardening.

Such systems can enhance production efficiency while reducing energy and water consumption. Significant progress has also been made in the field of horticultural robotics. Autonomous robots equipped with cameras and image-analysis modules are used for selective weeding, precise fertilization, and fruit harvesting. The integration of robots with neural networks enables the performance of delicate tasks-such as harvesting strawberries, tomatoes, or raspberries-that were considered technologically challenging only a decade ago [15]. In plant breeding, AI supports the selection of genotypes and phenotypes most resilient to environmental stress. The integration of image-based data with genetic information (multi-omics approaches) allows for shortening the time required to assess plant breeding value and increases the precision of selection [9]. In summary, the role of AI in horticulture is rapidly expanding, encompassing both precision crop management and the development of new cultivars. Implemented solutions indicate a trend toward integrated and autonomous systems, which enhance production efficiency while reducing costs and environmental impact.

Case Studies of Artificial Intelligence Implementations in Horticulture

To illustrate the practical dimension of artificial intelligence (AI) applications in horticulture, this section presents selected case studies of industrial and experimental implementations. The analysis encompasses examples from various types of crops, production systems, and scales of operation, allowing for the identification of both the benefits and limitations associated with AI integration.

Case 1: Automated Detection of Tomato Diseases in Greenhouses

In a commercial greenhouse producing tomatoes, a monitoring system based on high-resolution cameras and convolutional neural network models was implemented to identify early symptoms of late blight and powdery mildew. The system analyzed images in real time, generating alerts indicating the need for intervention. As a result, a reduction in staff response time and a decrease in crop losses by several dozen percent were observed. At the same time, it was demonstrated that the system's effectiveness depends on regular data calibration and the quality of lighting in the greenhouse [16].

Case 2: Microclimate Optimization in Vertical Farming

In an urban vertical farm, machine learning algorithms were used for dynamic control of environmental parameters, including photoperiod, humidity, and CO_2 concentration. The system processed data from sensors distributed across multiple levels of the structure, adjusting conditions to plant developmental stages. This implementation contributed to a reduction in electricity consumption by approximately 20% and improved uniformity of plant growth, which enhanced the repeatability of quality parameters in the harvested produce [17].

Case 3: Robotic Harvesting of Strawberries

In a farm specializing in strawberry cultivation, an autonomous harvesting robot equipped with stereo cameras and a fruit ripeness recognition module was employed. Using AI algorithms, the robot was able to selectively harvest ripe berries while minimizing mechanical damage. Compared to manual harvesting, lower variability in the quality of the collected fruit was observed; however, the robot's work efficiency remained lower than that of experienced pickers, indicating the need for further improvements in gripper design and decision-making models [18].

Artificial intelligence (AI) is playing an increasingly significant role in modern horticulture, offering tools that enhance production efficiency, improve crop quality, and increase the sustainability of cultivation processes. AI applications encompass plant condition monitoring, disease diagnostics, environmental control, automation of maintenance tasks, and support for breeding programs. The presented case studies demonstrate tangible economic and production-related benefits while simultaneously emphasizing the importance of data quality, system configuration, and user competence. Challenges include data standardization, model interpretability, infrastructure costs, and personnel training. The direction of future development points toward autonomous systems capable of independently optimizing cultivation processes in real time. Continued progress will require close collaboration among researchers, technology developers, and horticultural practitioners [19-23].

Conclusion

The integration of artificial intelligence into contemporary horticulture is transforming production systems by enabling more precise monitoring, decision-making, and automation. AI-driven tools facilitate early detection of plant diseases and abiotic stresses, optimize environmental control in greenhouses and vertical farms, and support the development of robotic harvesting systems that reduce labor dependency. Furthermore, data-driven approaches are accelerating breeding programs by improving the efficiency of phenotype and genotype analysis. Despite these advances, several challenges remain, including the need for standardized data collection frameworks, improved interpretability of AI models, and reductions in implementation costs to make these technologies accessible to a wider range of growers. Continued progress in this domain will require interdisciplinary collaboration between agronomists, computer scientists, engineers, and industry stakeholders. As digital infrastructure and agricultural data ecosystems continue to expand, AI is poised to play an increasingly central role in fostering sustainable, resilient, and high-efficiency horticultural production systems.

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