

Advances in Precision Horticulture for Enhanced Crop Productivity and Resource-Use Efficiency

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Abstract

Precision horticulture represents an advanced management approach that integrates modern technologies to optimize crop productivity, improve input-use efficiency, and enhance sustainability in fruit and vegetable production systems. With increasing pressure from climate change, resource scarcity, and the need for higher productivity, precision-based techniques offer targeted, data-driven solutions for horticultural management. This review examines recent advances in precision horticulture, including sensor-based monitoring, remote sensing, geographic information systems (GIS), Internet of Things (IoT), artificial intelligence (AI), variable-rate technologies, and decision-support systems. The role of precision irrigation, fertigation, pest and disease management, and protected cultivation in improving resource-use efficiency and crop performance is highlighted. Challenges, adoption constraints, and future prospects of precision horticulture are also discussed. The review emphasizes that precision horticulture is a key driver for sustainable intensification and resilient horticultural systems.

Keywords: Precision horticulture, smart farming, resource-use efficiency, sensors, remote sensing, sustainable horticulture.

1. Introduction

Horticulture plays a crucial role in ensuring food and nutritional security, income generation, and employment, particularly in developing countries. However, horticultural production systems face increasing challenges due to climate variability, declining natural resources, rising input costs, and environmental concerns. Traditional blanket-based crop management practices often lead to inefficient use of water, fertilizers, and pesticides, resulting in resource wastage and environmental degradation [1]. Precision horticulture has emerged as an innovative approach that applies advanced technologies to manage spatial and temporal variability within fields. By delivering the right input, at the right time, in the right amount, and at the right place, precision horticulture enhances crop productivity while minimizing environmental impacts [2]. The integration of digital tools and real-time data analytics enables informed decision-making and efficient resource management, making precision horticulture a cornerstone of modern sustainable agriculture.

2. Concept and Principles of Precision Horticulture

Precision horticulture is based on the recognition that variability exists within orchards, vegetable fields, and protected cultivation systems.

This variability may arise from differences in soil properties, topography, microclimate, crop growth stages, and pest pressure. The core principles of precision horticulture include observation, measurement, analysis, and site-specific management. Key components involve the use of sensors to collect data on soil moisture, nutrient status, canopy characteristics, and environmental parameters [3]. These data are analyzed using GIS, modeling tools, and AI-based algorithms to generate actionable recommendations. Precision interventions are then implemented through variable-rate technologies, automated irrigation systems, and targeted input application.

3. Sensor Technologies and Internet of Things (IoT)

Advances in sensor technologies have significantly improved the monitoring of horticultural crops and their growing environments. Soil sensors measure moisture, temperature, salinity, and nutrient levels, enabling precise irrigation and fertigation scheduling. Canopy sensors assess plant health, chlorophyll content, and stress levels, providing early warning signals for nutrient deficiencies or disease outbreaks [4]. The integration of sensors with IoT platforms allows real-time data transmission, storage, and analysis. Wireless sensor networks facilitate continuous monitoring across large production areas, including orchards and greenhouses.

IoT-enabled systems reduce labor requirements, enhance decision accuracy, and improve resource-use efficiency by enabling automated responses to changing field conditions.

4. Remote Sensing and Geospatial Technologies

Remote sensing technologies, including satellite imagery, unmanned aerial vehicles (UAVs), and drones, have transformed crop monitoring in precision horticulture. Multispectral and hyperspectral imagery provides detailed information on crop vigor, canopy temperature, leaf area index, and stress indicators. Vegetation indices such as NDVI are widely used to assess crop health and spatial variability [5]. GIS tools enable the integration of spatial data with field observations, allowing the creation of variability maps for targeted interventions. These technologies are particularly useful in perennial fruit crops, where long-term spatial variability influences yield and quality.

Table 1. Important precision horticulture technologies, their applications, and benefits

Precision Technology	Major Applications in Horticulture	Benefits for Crop Productivity and Resource-Use Efficiency
Soil moisture and nutrient sensors	Monitoring soil water status and nutrient availability	Optimized irrigation and fertigation, reduced water and nutrient losses
Remote sensing (satellite and UAVs)	Crop health assessment, stress detection, yield estimation	Early stress detection, improved decision-making, targeted management
Internet of Things (IoT) platforms	Real-time data collection and system automation	Reduced labor, timely interventions, efficient input use
Geographic Information Systems (GIS)	Spatial variability mapping and site-specific management	Precise input application, improved field-level planning
Variable-rate application technology	Site-specific fertilizer and pesticide application	Reduced input costs, minimized environmental impact
Decision-support systems (DSS)	Crop and resource management recommendations	Enhanced productivity, risk reduction, climate-smart management
Automated climate control systems	Temperature, humidity, and CO ₂ regulation in protected cultivation	Improved crop growth, consistent quality, higher yields

6. Precision Pest and Disease Management

Precision horticulture promotes targeted pest and disease management through early detection and site-specific interventions. Sensor-based monitoring, remote sensing, and image analysis tools enable the identification of pest infestations and disease symptoms at early stages. Decision-support systems provide recommendations for optimal control measures based on pest thresholds and environmental conditions. The integration of precision technologies with integrated pest management (IPM) strategies reduces pesticide use, minimizes resistance development, and protects beneficial organisms [7]. Precision spraying systems apply pesticides only where needed, improving efficacy and environmental safety.

7. Precision Horticulture in Protected Cultivation

Protected cultivation systems such as greenhouses and polyhouses benefit significantly from precision horticulture technologies. Automated climate control systems regulate temperature, humidity, light, and CO₂ concentration to optimize crop growth. Precision fertigation and hydroponic systems ensure efficient resource utilization and consistent crop quality [8]. Advanced data analytics and AI-driven models support crop scheduling, yield prediction, and quality assessment in controlled environments. Precision horticulture enhances productivity, reduces input costs, and improves sustainability in high-value horticultural crops grown under protected conditions.

Remote sensing enhances early detection of stress and supports site-specific management decisions.

5. Precision Irrigation and Fertigation

Water and nutrient management are critical components of precision horticulture. Precision irrigation systems such as drip and micro-sprinkler irrigation deliver water efficiently to the root zone, reducing losses through evaporation and runoff. Soil moisture sensors and weather-based models help schedule irrigation according to crop water requirements [6]. Fertigation allows the precise application of nutrients through irrigation systems, improving nutrient uptake and reducing leaching losses. Variable-rate fertigation adjusts nutrient doses based on crop growth stage and soil fertility status. These practices enhance water- and nutrient-use efficiency, improve crop quality, and reduce environmental pollution.

8. Challenges and Adoption Constraints

Despite its benefits, the adoption of precision horticulture faces several challenges, including high initial investment costs, limited technical expertise, and inadequate infrastructure. Small and marginal farmers may find it difficult to adopt advanced technologies without institutional support. Data management, interoperability of devices, and lack of standardized protocols also pose challenges. Capacity building, extension services, and policy incentives are essential to overcome these barriers. Public-private partnerships and affordable technology solutions can facilitate wider adoption of precision horticulture practices.

9. Future Prospects and Conclusion

The future of precision horticulture lies in the integration of AI, machine learning, big data analytics, and robotics to further enhance decision-making and automation. Advances in low-cost sensors and user-friendly platforms are expected to improve accessibility for smallholder farmers. Precision horticulture will play a pivotal role in sustainable intensification by enhancing productivity, resource-use efficiency, and environmental stewardship. precision horticulture represents a transformative approach for modern fruit and vegetable production. By leveraging advanced technologies and data-driven management, precision horticulture contributes to resilient, efficient, and sustainable horticultural systems capable of meeting future food and nutritional demands.

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