

## Precision Horticulture: Sensor-Based Canopy, Root-Zone, and Post-Harvest Management for Quality Improvement

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### Abstract: -

The production of horticultural crops such as fruits, vegetables and ornamentals requires a high level of control over the various growth conditions to produce quality crops and high value in the market. The old system of horticulture is very dependent on the experience and the eye of the farmer, which is becoming ineffective as farmers strive to achieve maximum outputs at minimum water, fertilizer and pesticide application. Precision horticulture is an all-encompassing approach that incorporates sensor technology, Internet of Things (IoT) infrastructure, and data analytics to provide real-time monitoring and control of the canopy conditions, root-zone moisture and nutrition, and the quality of post-harvest. Machine learning-based spectral sensors detect nutrient deficiency, disease, and pest infestations with over 90 percent accuracy; thermal imaging detects water stress without destruction; soil moisture sensors are used to control irrigation, saving 30-40 percent of water; variable rate machine spraying is used to reduce the use of pesticides by 40 percent; post-harvest IoT monitoring using methane gas sensors is used to monitor ripeness and decay; and variable-rate machine spraying is used to reduce the use of pesticides by 40 percent. This paper scrutinizes canopy monitoring systems, technologies of managing root-zones, post-harvest quality assurance strategies and implications of these to the enhancement of horticultural quality improvement and sustainability.

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**Introduction:**

Horticultural crops fruits, vegetables, and ornamentals are high-value agricultural elements of the global agricultural system, yielding significantly more income per hectare than field crops and being important sources of micronutrients, vitamins, and dietary diversity to the global populations. Nevertheless, there are some special intensive production problems with horticulture. Horticultural systems are used in contrast to annual field crops with lower densities, with intensive production, which may be a number of crops or a perennial crop requiring long-term management in years or decades. The issue of quality goes past quantity: consumers and buyers expect fruit without blemishes, vegetables at a stage of maturity of optimal harvest, ornamentals of a quality in the aesthetic consideration that goes far beyond the quality needed by field crops. To meet high horticultural quality and handle the rising water-stressed, nutrient - stressful environments, sophisticated and data-driven management is required. Precision horticulture is the use of spatial and temporal precision technology to maximise horticultural production. Growers detect the early signs of stress, lack of nutrients or disease that can be treated at an early stage when it is only effective to treat. Root-zone meters maintain efficient irrigation and fertilizing of plants to

exact needs without wastage. The post-harvest monitoring systems are used to monitor the stages of ripeness, decay and cold chain integrity making sure that only quality products are delivered to the consumers. This article evaluates the role of sensor-based precision horticulture in improving the quality of products, resource use and sustainability in production and after the harvest period.

**Canopy Monitoring: Real-Time Detection of Stress, Disease, and Nutritional Status**

The leaves of the plant canopy and the growing shoot will give constant information about the state of plant health and stress. Horticulture technologies use these signals to transform them into actionable information, which can be used to implement management interventions in time.

**Nutrient and Stress Spectral Sensing:** Spectral sensors that record plant reflectance at different wavelengths can be used to identify physiological changes before the onset of any observable symptoms. The spectral effects of different nutrient deficits have typical spectral patterns: the spectral pattern of nitrogen deficit differs from the spectral pattern of potassium deficit or iron deficit. Machine learning algorithms that are trained using thousands of spectral images of recognized nutritional deficiency and healthy plants find specific nutrient restrictions with a >90% accuracy. Equally, water stress

generates small spectral variations that become visible days before visible wilting is seen. When a problem is identified early, it can be corrected by adding fertilizers or irrigating accordingly before the quality of a product becomes compromised, and it is also possible to distinguish between high-quality and stressed products that have low quality.

**Thermal Imaging to detect Water Stress:** The temperature of the leaf is sensed by the thermal infrared cameras and rises when plants are stressed by water and the stomatal closure restricts evaporation to cool the plants. Canopy temperature sensors detect areas of water stress in the fields or greenhouses, and allow targeted irrigation intervention. This non-destructive measurement is especially useful in horticultural systems that are intensive where the time of irrigation plays an important role in determining the quality of fruits, flavor development and maturity at harvesting.

**Disease and Pest Detection:** Image analysis systems based on machine learning identify early signs of fungal diseases, bacterial pathogens and pest infestation on photographs or through continuous video surveillance. Farmers take photos of suspicious spots or lost foliage; the system gives the identification and control advice regarding the disease. In plants with high horticultural crops susceptible to widespread

disease, rapid disease outbreaks are inhibited by early disease identification which shortens the detection-to-intervention interval and thus results in disease epidemics devastating crops and quality.

**Hyperspectral Sensors to Phenotyping:** The use of hyperspectral imaging, which involves the recording of reflectance data in many dozens of wavelengths, is an advanced method of phenotyping plants through detailed characterization of physiological status. Such systems allow tracing small differences in photosynthetic efficiency, resource allocation and tolerance to stress among varieties or selection lines and can breed better cultivars faster.

**Root-Zone Management: Accuracy Irrigation and Nutrient Management** Canopy monitoring focuses on the conditions observed above the ground whereas root-zone sensors give a continuous report regarding the soil moisture, nutrient availability, and the condition of the growing medium contributing to the quality and productivity of the plants.

**Soil Moisture Monitoring and Irrigation Scheduling:** Capacitive and tensiometric soil moisture sensor is mounted at various depths of the soil and constantly measures the availability of moisture. Combination of these measurements and crop

specific water demand models facilitates accurate irrigation planning. Instead of using a unified time-based water application, the scheduling and the amount of irrigation changes according to the real state of the soil and the phenological stage of the crop. Research has shown that soil moisture sensor-based irrigation results in 30-40 percent water conservation in contrast to traditional scheduling whilst yielding no harm or even improvement in yield and quality. This efficiency is essential in areas of water scarcity where the lack of water in production horticulture competes with the municipal and industrial water demands.

**Precision Fertilization:** Soil nutrient sensors measure the available nitrogen, phosphorus and potassium, yet these sensors are still not as advanced as the moisture monitors. Fertility management is more usually combined with soil test analysis, tissue nutrient evaluation, and visual observation of plants. Nevertheless, dynamic adjustment of fertilizers can be carried out with the help of real-time systems to track the leachate nutrient levels in intensive greenhouse and nursery systems. Fertigation systems that combine water and dissolved nutrients enable concentration of nutrients to be adjusted on a minute-by-minute basis. All the surplus fertilized flows into groundwater polluting it and lacking the right amount of fertilizer

inhibits growth and quality. Fertirrigation is also optimized in order to balance productivity with the protection of the environment and at a minimal cost of fertilizer.

**Root-Zone Temperature Control:** In certain types of horticultural crops, root-zone temperature has a profound effect on the results of quality. Root-zone temperature also affects strawberry development of flavor, color development in fruits, and root pathology. Root-zone temperature control as well as moisture and nutrient optimization in high value crops can be achieved by use of heated or cooled irrigation systems.

**Variable-Rate Application: Canopy Management in Focus**

In addition to monitoring, precision horticulture systems have provided the ability to initiate and control location-specific applications that minimize chemical input and enhance efficacy.

**Variable-Rate Pesticide Application:** Canopy density in individual positions is measured by ultrasonic or LiDAR sensors, and the spray systems apply varying pesticide application rates with higher concentrations applied to canopy areas that need more coverage, and low rates applied in thin areas. This type of variable-rate spraying results in 30 to 40 percent less pesticide spraying as compared to uniform spraying and still retains the same level of disease or pest control.

Lowering the chemical application improves the economics of growers, minimizes the level of residue on the harvest, and lessens the environmental impact.

**Targeted Nutrient Application:** In non-homogenous orchards of differing canopy density and soil fertility, variable-rate application of fertilizers optimizes the supply of nutrients to regions with high demand and holds back excessive application in regions with low demand. This accuracy saves on the overall amount of fertilizers used and enhances the uniformity of fruit quality throughout the orchard.

### **IoT-Based Implementation of Post-Harvest Quality Assurance**

Quality is also perpetuated after harvest with the help of post-harvest handling, storage, and distribution channels. Monitoring systems IoT-based are used to monitor temperature, humidity, ripeness indicators, and signs of decay between harvesting and consumer delivery.

**Methane Gas Sensing of Ripeness and Decay:** Ethylene is a plant hormone that induces ripening cascades, and it is emitted by ripening fruits; methane and other fermentation volatiles are emitted by over-ripening or rotting produce. Sensors of methane gas that is installed in cold storage facilities and transportation containers detect volatile organic compounds that signify the

ripeness phase and decay rates. Retail or consumer markets are no longer exposed to deteriorated produce and automated systems can separate this produce and minimize postharvest losses (20-30% of many fruits and vegetables in developing countries) at the same time as quality standards are achieved on delivered produce.

### **Temperature and Humidity**

**Monitoring:** IoT devices in cold chains constantly monitor temperature and humidity. Change in temperature that causes quality loss or pathogen proliferation triggers instant warning, which allows preventive intervention before the extent of produce damage is severe. Stored data on cold chain history would be used to determine traceability and assign liabilities in case quality problems arise.

**Cold Chain Integrity:** Real-time tracking to know when refrigerating systems go awry or when the door is left open too long, and the quality will not be compromised due to abuse of temperatures. Cold chain integrity is essential in the preservation of the quality of produce that is time sensitive, such as a berry or a leafy vegetable.

**Shelf-Life Prediction:** Predominantly trained on harvest data, machine learning models tend to predict the remaining shelf-life with acceptable accuracy, using post-harvest data to forecast maturity, temperature history and humidity exposure, allowing retailers to

time their sales and reduce the amount of waste. Before shelf-life expiry, producers and distributors are notified in advance to allow promotion of pricing or other markets before they go to waste.

### **Quality Improvement Outcomes and Sustainability Benefits**

The precision horticulture systems show some effectiveness in the improvement of the quality of horticulture and the minimization of environmental impact by the use of integrated systems. The research and commercial implementation document:

#### **Enhanced Quality Consistency:**

Advanced canopy and root-zone control leads to stress-induced quality fluctuation; crop matures at the most ideal maturity with better flavor, color, and nutritional information.

#### **Less Chemical Applications:**

Variable-rate application and early disease-detection make possible 30-40 percent reduction in the use of pesticides and fungicides.

#### **Water Conservation:**

Precision irrigation consumes 30-40% less water and does not compromise quality.

#### **Postharvest Loss Reduction:**

IoT quality monitoring and decay detection can minimize postharvest losses by 15-25%.

#### **Longer Market Access:**

Better consistency and quality allow reaching

higher quality markets and longer distances of distribution raising farmer income.

### **Implementation Opportunities and Challenges**

Precision horticulture adoption has various obstacles to adoption in developing country settings despite the possible advantages.

**Infrastructure Investment:** Sensor systems, IoT infrastructure, data analytics platforms and training is an important investment. Such technology is not usually available to small holder horticultural farmers.

Potential solutions are provided by shared service models, equipment commonly owned by farmer groups or cooperatives.

#### **Technical Knowledge and Literacy:**

Technical knowledge is a kind of capacity that is needed to operate sensor systems and reading of data, and most of the smallholder producers lack this kind of capacity. It is important to integrate with extension services and technical support organizations.

**Data ownership/data privacy:** With systems gathering comprehensive farm and producer data, the issue of the ownership, privacy, and misuse of this data should be considered. Clear data management systems safeguarding the farmers are required.

#### **Diversity and Crop-Specific**

**Calibration:** The precision horticulture

systems should be tuned to crop varieties, growing environment, and quality requirements in the market. Generic systems are not optimally good; local calibration and validation is still necessary.

### **Suggestions on the Successful Implementation**

In order to optimize the benefits of precision horticulture to maximize quality improvements and to allow smallholder farmers to adopt the technology, a number of actions should be given priority:

**Public Investment in Shared Infrastructure:** Government policies to support shared sensor systems, data platforms and extension integration can lower the cost barriers.

**Capacity Development Farmer:** Educational programs that allow farmers to learn how the system works and read data are crucial.

**Farmer-Participatory System Development:** The relevance and adoption of quality priorities in system design can be achieved through the involvement of producers in system operating definition.

**Extension Services:** Extension workers who have been trained in precision horticulture are able to offer support to farmers and facilitate access to technology.

### **Sustainability Standards Alignment:**

Economics A connection of precision horticulture activities to sustainability certification and premium market access is created which would be an economic incentive towards adoption.

### **Conclusion**

The phenomenon of precision horticulture, which uses sensor-measured canopy, root-zone, and post-harvest quality to improve quality, is a shift in the paradigm of the horticultural crop attaining high quality by utilizing environmental resources in a sustainable way. Spectral sensors with >90% nutrient deficiency, disease, and stress detection; non-destructive thermal imaging to detect water stress; soil moisture sensors to allow saving of 30-40% of irrigation water; variable-rate spraying to save up to 40% on pesticides; and post-harvest IoT systems that prevent the loss of quality of harvest through ripeness and decay detection change horticultural production. The technologies are especially helpful in horticultural crops that depend on quality directly on market value and income of the farmer. Precision horticulture has a role to play in the context of developing countries where population growth increases the demand of nutritious horticultural produce, production can be intensified with less water, minimal chemicals and less after harvest loss. This needs to be implemented through

infrastructure, capacity development of the farmers and engagement with the extension services, yet is becoming evident in terms of returns on investment through quality premiums, resource savings, and waste reduction. Precision horticulture technologies when implemented with responsiveness to farmer demand, local capacity and equitable access are likely to increase food security, environmental sustainability, and farmer livelihoods by improving the quality of horticulture output and efficiency of resources.

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