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Smart orchard management: Precision technology for sustainability and quality fruit production

Smart orchard management has emerged as a cutting-edge concept that integrates sensor technology, weather monitoring, the Internet of Things (IoT), automation, decision-support tools, and traceability to optimize orchard operations. ICAR-CISH, Lucknow, has developed smart orchards for mango and guava to modernize subtropical fruit production systems. Unlike conventional practices, smart orchard systems employ real-time monitoring, predictive analytics, and automation to provide site-specific decisions that enhance productivity, fruit quality, and resilience to climate change. By adopting sensor-based monitoring of soil moisture, plant health, and weather parameters, along with precision irrigation, targeted integrated pest management (IPM), and AI-powered decision support, mango and guava orchards can achieve higher productivity, improved fruit quality, and reduced environmental impact.

Keywords: Digital decision support, IoT-enabled sensors, Multispectral imaging, Smart irrigation, Traceability systems

Smart orchard management represents a modern approach to fruit production that integrates digital technologies, precision farming tools, and climate-smart practices to enhance productivity, quality, and sustainability. Traditional orchard systems often face challenges such as inefficient water and nutrient use, pest and disease outbreaks, and variable fruit quality. With the advent of sensor networks, IoT-enabled devices, multispectral imaging, automated irrigation systems, and AI-based decision support, orchards can now be monitored and managed with greater accuracy and efficiency. These technological interventions not only optimize resource use but also reduce carbon and energy footprints, improve resilience to climate variability, and ensure safer, traceable, and market-ready fruits.

ICAR-CISH, Lucknow, has developed smart orchards of mango and guava by integrating sensor technology, multispectral imagery, canopy management, and precision management of nutrients, water, and pests. These orchards modernize subtropical fruit production by enhancing yield, fruit quality, traceability, and sustainability while reducing input costs and post-harvest losses.

SENSOR TECHNOLOGY

Sensor technology refers to the use of electronic or mechanical devices that detect, measure, and transmit information about environmental and plant conditions in fruit production systems. These technologies help farmers make precise, real-time decisions regarding irrigation, nutrient management, pest control, harvesting, and post-harvest handling. By generating accurate data, sensors minimize resource wastage, and improve fruit yield, quality, and sustainability.

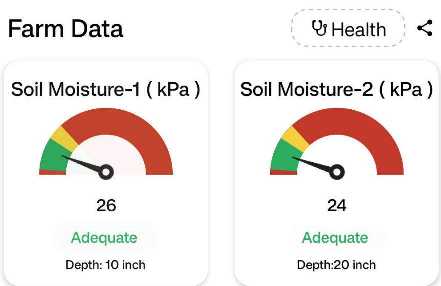
Types of sensors used in fruit production

A. Soil sensors

- ***Soil moisture sensor:*** Measure soil water potential to optimize irrigation scheduling.
- ***Soil temperature sensor:*** Help determine root zone temperature for better nutrient uptake.

In fruit orchards (mango and guava) irrigation scheduling is primarily based on fixed calendars and visual plant stress symptoms such as over-irrigation is common leading to waterlogging, nutrient leaching and soil borne disease such as collar rot. Sensor-based soil moisture monitoring in root zone of mango and guava offers a robust solution by enabling real-time measurement of soil-water dynamics. This technology ensures optimum application of irrigation water improve water use efficiency (WUE), and reduce the environmental footprint in mango and guava production system.

IoT-enabled sensors keep a track of soil water potential at multiple depths to inform irrigation scheduling. In mango and guava feeder roots are concentrated at 40–50 and 25-30 cm, so water potential measured near this depth is the most representative indicator of crop water status. Maintaining the soil water potential between −15 to −35 kPa (near field capacity, soil-texture dependent) is optimal. Values less negative than −15 kPa indicate a wet profile, while values more negative than −35 kPa indicate dry soil needing irrigation. It has been observed that, sensor-based irrigation saves around 25-30% water in mango, thus enhancing water use efficiency. In comparison to control, irrigation scheduling with sensor enhances



Soil moisture potential in mango and guava under different conditions

Soil moisture condition	Soil water potential	Remarks
Dry soil	< -35 kPa	Drought stress
Saturated	-15 to -35 kPa	Optimum plant growth
Wet soil	>-15 kPa	Leaching of nutrients

B. Weather sensor

Weather sensor is specialized devices used to monitor atmospheric parameters that directly influence crop growth, pest and disease incidence, and fruit quality. In fruit orchards, they are often integrated into automated weather stations (AWS) or IoT-based systems to provide real-time, site-specific data for decision-making. Weather sensor predict temperature, humidity, radiation, leaf wetness, rainfall, wind speed and evapotranspiration which are highly useful for crop production.

Weather sensor in mango plot of ICAR-CISH

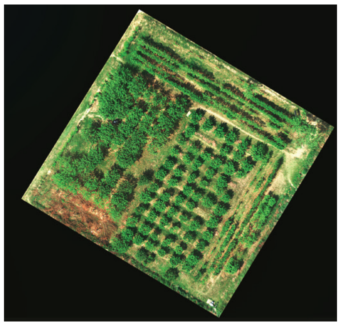
Significance

- Weather data (ET from temperature, humidity, solar radiation, wind speed) is used with crop coefficients to calculate crop water requirement.
- Integration of temperature, humidity, rainfall, and leaf wetness helps forecast risk of diseases such as anthracnose in mango.
- Temperature-based growing degree days (GDD) facilitate the prediction of flowering, fruit set, and maturity stages.
- GDD predicts the optimum stage of fruit maturity in mango, as delayed harvesting affects fruit quality and marketable yield.
- Wind sensor determine safe spraying windows to reduce pesticide drift.

C. Multispectral imaging sensor

Multispectral imaging (MSI) is an advanced remote sensing technology that captures image data at visible (VIS), near-infrared (NIR) and short-wave infrared regions. Multispectral sensors capture reflectance at key bands, allowing calculation of vegetation indices such as NDVI, SAVI and GNDVI. In horticulture, MSI has gained prominence as a non-destructive, rapid, and precise tool for monitoring crop health, detecting stress, assessing yield potential, and improving resource-use efficiency. Multispectral imaging system generates different types of images related to overall plant vigor that help to detect visible stress, chlorophyll-related issues, crop health and vitality. This technology helps farmers make data-driven decisions to improve crop yields and resource management by identifying issues like nutrient deficiencies, diseases, and water stress earlier than visual inspections, leading to more efficient, sustainable and productive farming practices. Moreover, MSI enables targeted applications of fertilizers, pesticides, and water, reducing waste and environmental impact by providing detailed information at a field-specific level.

Drone-based multispectral imaging system



Multispectral image of mango orchard of ICAR-CISH, Lucknow

CANOPY MANAGEMENT

Canopy management is the central pillar of smart orchard management because it governs how efficiently

Espalier training system in guava at ICAR-CISH

Optimized canopy of mango under high density planting at ICAR-CISH

Technological integration in smart orchard management

Technology	Description	Significance
IoT-based sensor system	Monitoring of soil moisture, temperature, humidity, solar radiation, etc.	- Water and nutrient use efficiency increased by ~20%. - Fruit yield increased by ~15% due to precise canopy and input management. - Carbon footprint reduced by ~20%. - Replicable model for high-density and rejuvenated elderly mango orchards.
Canopy architecture	Regulation of canopy according to tree density and condition	Optimizes light interception, improves fruit quality, and reduces pest and disease incidence.
Automated weather station	Real-time weather data for decision-making on pest management	Enables timely interventions for pest and disease control.
Smart irrigation	Automated irrigation and fertigation based on crop need	Improves water-use efficiency and ensures precise nutrient application.
Multispectral imaging and Drone technology	Tree health monitoring and pest management	Facilitates early stress detection, yield estimation, and targeted management.
QR code system	Data documentation and traceability	Ensures farm-to-fork traceability and transparency in orchard management.
Mobile-based dashboard	Agronomic practices, decision support system	Provides real-time advisories on irrigation, nutrients, and pest management.

a fruit tree captures sunlight, uses water and nutrients, withstands stresses, and produces marketable fruit. Canopy management involves regulating tree architecture and foliage to maximize light interception, improve fruit quality, and reduce pest and disease incidence. For example, the espalier training system in guava enhances light penetration, air circulation, and nutrient use efficiency, resulting in higher yields and better-quality fruit. Its open structure also lowers pest and disease incidence, facilitates pruning, spraying, and harvesting, and is well suited for high-density planting.

In smart orchards, canopy management is data-driven and technology-assisted, moving beyond traditional pruning into precision canopy design. Smart canopy management of mango and guava integrates leaf wetness sensors, drones, and imaging tools to monitor canopy microclimate. Additionally, data on solar radiation and canopy density help maintain an optimal leaf area index (LAI) for maximum photosynthesis and fruit coloration. Smart pruning and canopy reconfiguration in mango and guava thus create conditions conducive to high-quality fruit production.

DIGITAL TOOLS

Smart orchard management leverages digital technologies to transform orchards into data-driven, traceable, and climate-smart systems. Key digital tools—software platforms, mobile apps, dashboards, and QR codes (Quick Response codes)—play a crucial role in record keeping, traceability, decision-making, and ensuring consumer confidence.

- **Mobile-enabled dashboards:** Allow farmers to access real-time updates on irrigation requirements, nutrient status, pest risk alerts, and weather advisories.
- **Integration of multispectral image maps:** Provides orchard block layouts showing canopy density, vigor index, and yield estimation.
- **Software platforms:** Integrate sensor, weather, and soil data to deliver actionable advisories, such as optimal irrigation timing and pesticide application schedules.
- **Digital tools for traceability:** Document farm-to-fork practices, including input usage and orchard management activities.
- **QR codes:** Offer detailed information on orchard management practices followed during production, enhancing transparency and traceability of the fruit production system.

Smart mango orchard at ICAR-CISH

TECHNOLOGICAL INTEGRATION

By enabling precise irrigation, nutrient application, pest management, and tree health monitoring, smart tools enhance overall resource-use efficiency. Smart sensing and imaging technologies further improve fruit quality and marketability, which is vital for both domestic and export markets. Importantly, these interventions help minimize pesticide residues and conserve water and energy. Beyond production, digital tools and traceability systems ensure food safety, transparency, and build consumer trust.

CONCLUSION

Smart orchard management in mango and guava has the potential to bring a paradigm shift in fruit production by integrating digital innovations with sustainable practices. By adopting sensor-based irrigation scheduling, precise nutrient management, targeted integrated pest management (IPM), and AI-powered decision support, orchards can achieve higher productivity, improved fruit quality, and reduced environmental impact. This approach not only enhances farmer profitability but also contributes to climate-smart fruit production. In essence, smart orchard management represents more than a technological upgrade–it is a holistic transformation of fruit production systems. However, large-scale adoption will require stakeholder collaboration, skill development, and the creation of cost-effective technologies.

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