

Smart postharvest management of horticultural crops through digital solutions

Digital tools such as sensors, Internet of Things (IoT) devices, blockchain, and data analytics offer effective solutions to several challenges, ensuring crops maintain their quality and freshness throughout the supply chain. IoT-based cold chain solutions are gaining importance in India. These systems alert farmers and distributors when conditions are not optimal, helping reduce spoilage during storage and transit. Data-driven insights that assist farmers in making informed decisions about harvest timing, storage, and market prices offers solution for profitability and sustainability. By using satellite imagery, weather data, and predictive analytics, it is possible to optimize postharvest management practices, helping reduce losses and improve profitability for Indian farmers. In food processing, digital technologies are also transforming operations. Automated systems with IoT sensors and AI algorithms enhance efficiency and quality. Blockchain technology is another vital tool being explored to enhance traceability in India's supply chain and provide end-to-end traceability, ensuring that both domestic and international consumers receive high-quality produce. This is particularly valuable for exports, which must meet strict quality and safety standards.

IN today's fast-paced world, the rapid advancements in technology have significantly influenced the field of horticulture, which encompasses both perennial and annual crops, including a wide range of fruits, vegetables, flowers, spices, plantation crops, nuts, and exotic crops. Although horticulture occupies a smaller land area compared to other agricultural sectors, it stands out for its high economic and nutritional value. Over the past decade, the area dedicated to horticulture in India has increased by 2.6% annually, while production has risen by 4.8%. Horticulture occupies 10% of the land in India, besides contributes over 34.4% of the agricultural GDP and supports nearly 20% of the agricultural labour force, besides occupying less than 12.5% of the total cropped area. The importance of postharvest management in horticultural crops cannot be overstated. Unlike food grains, horticultural crops such as fruits, vegetables, and ornamental plants are highly perishable and susceptible to rapid quality deterioration after harvest. Proper postharvest management is critical for minimizing losses, maintaining quality, ensuring food safety, and extending the shelf-life of these products. Globally, postharvest losses are a significant issue, often accounting for 35-40% of production in different commodities.

Conventional postharvest management systems face several challenges that limit their effectiveness. Many traditional methods rely heavily on manual handling, subjective quality assessment, and rudimentary storage practices, which can lead to inconsistent quality control

and significant postharvest losses. Additionally, traditional methods are labour-intensive and costly, limiting scalability, especially in regions with limited access to modern technology. Inadequate infrastructure, such as cold chain systems and packaging technologies, further exacerbates these losses, where access to advanced storage and transportation facilities may be limited. Other issues include the lack of real-time monitoring, inadequate pest and disease control, and the difficulty in predicting optimal harvesting times, which can lead to over-ripening or under-ripening of crops. With increasing global demand for food and rising pressures on natural resources, it is critical to adopt more efficient, sustainable, and scalable solutions.

Digital technologies application in PHM

Digitalization refers to the integration of digital technologies into horticultural practices, enabling stakeholders to collect and analyze data in real-time. The advent of digital technologies has now transformed how postharvest management is carried out, offering innovative tools to address many of the issues faced by conventional systems. Technologies such as the Internet of Things (IoT), artificial intelligence (AI), blockchain, and big data analytics offer real-time, precise monitoring of crop conditions during storage and transportation, enabling timely interventions to maintain product quality and minimize losses. The Internet of Things (IoT) connects various devices and sensors within agricultural

settings, allowing for the real-time monitoring of crops and environmental conditions. This continuous flow of information helps farmers make timely decisions regarding irrigation, fertilization, and pest control, ultimately leading to improved postharvest quality and reduced losses. The buzzwords, Artificial Intelligence and Machine learning (AI and ML) process vast amounts of data from various sources, identifying patterns and making predictions about crop yields, pest infestations, and disease outbreaks. For example, ML algorithms can analyze historical weather data and crop performance to predict optimal harvest times, enhancing postharvest management by ensuring that crops are harvested at their peak quality. Cloud computing provides a centralized platform for storing and analyzing vast datasets related to postharvest management. Big data analytics enables stakeholders to identify trends, monitor performance, and optimize processes. Blockchain enhances transparency and traceability in horticultural supply chains. By creating a secure, decentralized ledger of transactions, blockchain allows all stakeholders—producers, distributors, retailers, and consumers—to track the journey of crops from farm to table. This is particularly beneficial in postharvest management, as it ensures the integrity of product quality and safety, enabling stakeholders to verify the origin and handling of horticultural crops throughout the supply chain. Automation plays a significant role in the postharvest phase, especially in packing and sorting. Robotic systems can handle delicate fruits and vegetables with precision, ensuring minimal damage during the packing process. Automated sorting systems equipped with AI can analyze colour, size, and quality, categorizing products for optimal market distribution. This reduces human error and enhances the efficiency of postharvest operations. Drones are increasingly utilized in postharvest management for tasks such as monitoring storage facilities and assessing the health of crops before they are harvested. They can provide high-resolution imagery and data on crop conditions, allowing for better planning of postharvest processes. Additionally, drones can be used for targeted applications of protective treatments during the postharvest phase, ensuring that crops remain disease-free during storage and transport.

Smart sensors-based solutions for postharvest supply chain management

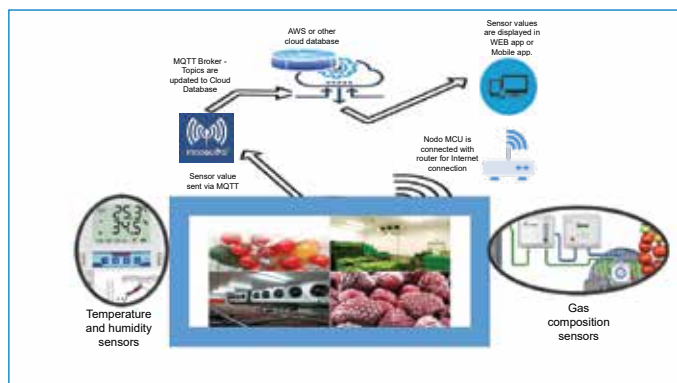
Quality and grading of fruits and vegetables: Traditional methods of quality assessment often rely on human inspectors, which can be time-consuming and subjective. Quality and grading assessments of fruits and vegetables are increasingly relying on AI-driven techniques to ensure consistency and accuracy. Convolutional neural networks (CNNs) are particularly effective for image recognition tasks, enabling the automated grading of produce based on visual attributes such as size, colour, and surface defects. For instance, a CNN can be trained on a labeled dataset containing images of high-quality and low-quality fruits. This automation not only enhances the efficiency of grading processes but also reduces human error, ensuring that only the highest-quality products reach consumers. Further, techniques such as image processing combined with ML algorithms can identify physical defects such as

bruises, blemishes, or inconsistencies in shape and size. However, using algorithms like support vector machines (SVMs) or decision trees, ML systems can analyze image data to detect anomalies with a high degree of accuracy. Moreover, advanced unsupervised learning techniques, such as clustering algorithms, can also be employed to identify anomalies in large datasets without the need for labeled training examples. These algorithms can detect outliers that deviate significantly from expected patterns, which may indicate defects or spoilage.

Smart sensors for real time monitoring and cold chain logistics and processing: Monitoring cold chain logistics is a critical component in the postharvest management of horticultural crops, ensuring that products maintain their quality and safety from the point of harvest to the final consumer. Smart sensors are integral to modern postharvest management, providing accurate and timely data that allow for informed decision-making. A smart sensor is a device that takes input from the physical environment and uses built-in compute resources to perform predefined functions upon detection of specific input and then process data before passing it on. In smart storage facilities, a network of IoT devices is employed to continuously monitor critical environmental parameters such as temperature, humidity, and gas composition. Sensors are strategically placed throughout storage areas to gather real-time data, allowing for precise control over the storage environment.

Temperature and humidity sensors are deployed within storage facilities and transport containers to continuously monitor environmental conditions. Typically, these sensors use thermocouples or thermistors to measure temperature and hygrometers to gauge humidity levels. These sensors transmit data via wireless protocols (e.g. Zigbee, Wi-Fi) to a centralized monitoring system. The system can analyze the data in real time and trigger alerts if conditions deviate from pre-defined thresholds. For instance, maintaining a temperature of 0-4°C for fruits like strawberry can significantly prolong its shelf-life. If the temperature rises above 4°C, automated notifications can prompt corrective actions, such as adjusting cooling systems or redistributing products to maintain optimal conditions. Additionally, the integration of GPS tracking with cold chain monitoring systems enhances visibility and control throughout the transportation process. By combining location data with temperature and humidity readings, logistics managers can track not only where the shipment is but also the conditions it is experiencing at any given moment.

Gas composition sensors utilize electrochemical or infrared detection technologies to monitor gases such as oxygen (O₂), carbon dioxide (CO₂), and nitrogen (N₂) in controlled atmosphere storage. These sensors are installed in storage chambers where the atmospheric composition is adjusted to slow down respiration and ripening processes. Real-time adjustments to gas mixtures can be made based on sensor feedback, optimizing conditions for different types of produce. Ethylene sensors, often based on metal oxide semiconductor (MOS) technology, detect concentrations of ethylene gas emitted by ripening fruits. By integrating these sensors into storage and packing



Sensor and IoT based monitoring of postharvest quality of fresh produce

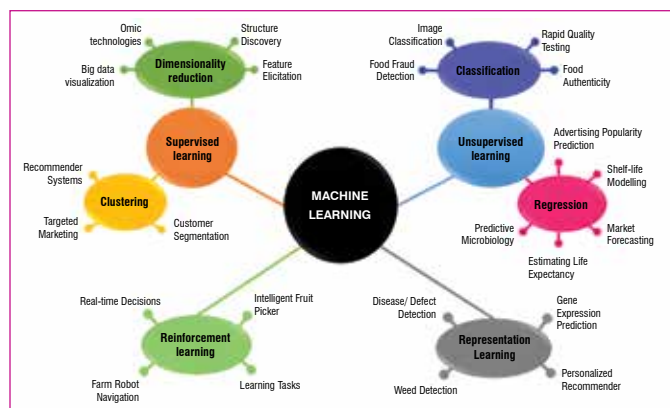
areas, stakeholders can manage ripening schedules more effectively. Furthermore, analyzing historical data collected from these shipments can provide insights into patterns and trends that inform future logistics strategies. Predictive maintenance alerts can be generated if temperature fluctuations occur frequently, indicating potential equipment malfunctions before they lead to costly failures.

Intelligent packaging solutions: By incorporating active and smart features, intelligent packaging systems can interact dynamically with their environment, ensuring that the produce remains fresh and safe for consumers. Smart packaging technologies incorporate sensors and indicators that provide real-time feedback on the condition of the produce. Time-temperature indicators (TTIs) signal if products have been exposed to temperatures outside of safe limits, changing colour when specific thresholds are exceeded. Freshness indicators monitor spoilage-related volatile organic compounds (VOCs) through E-nose and can visually indicate the decline in product quality. Furthermore, integrating QR codes or Near Field Communication (NFC) technology allows consumers to access detailed information about the product's journey, including its origin, handling conditions, and freshness history. This level of transparency builds consumer trust and promotes accountability among retailers. IoT-enabled sensors continuously track parameters such as temperature, humidity, and gas concentrations, transmitting real-time data to cloud-based platforms for analysis. This capability allows stakeholders to respond promptly to deviations, minimizing the risk of spoilage. Additionally, the data collected can optimize supply chain logistics, enabling predictive models that anticipate potential quality issues and adjust logistics strategies accordingly.

Machine Learning for decision making

Machine learning (ML) has emerged as a powerful tool in postharvest decision-making, significantly enhancing the management of horticultural crops. By leveraging predictive models, quality assessment techniques, and defect detection algorithms, ML can optimize storage practices, improve product quality, and reduce waste, which are particularly relevant in the context of rapidly evolving agricultural markets and increasing consumer demand for high-quality produce.

Predictive models for shelf-life estimation: Predictive models for shelf-life estimation utilize historical data to



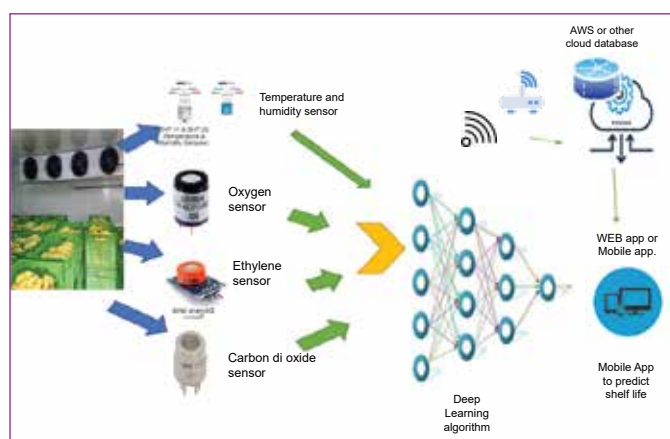
Machine learning for various applications in horticulture

forecast the remaining viability of fruits and vegetables. Machine learning algorithms, such as regression analysis, support vector machines (SVM), and neural networks, are employed to analyze factors influencing shelf-life, including temperature, humidity, and ethylene concentration. More advanced models, like artificial neural networks (ANNs), can handle complex, non-linear relationships, making them well-suited for this task. By training these models on extensive datasets that encompass various environmental conditions and their effects on different produce, stakeholders can accurately predict how long a product will remain marketable. This information allows for better inventory management and more informed decisions regarding transport and storage.

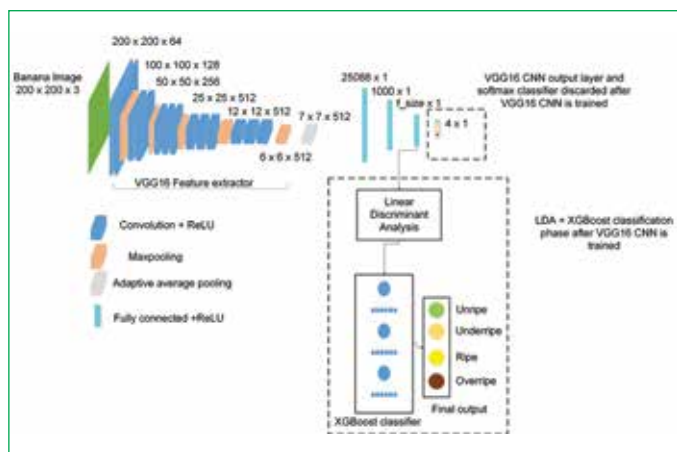
CNN-XgBoost approach offers a reliable and efficient method for non-destructive ripening stage classification of bananas. Its ability to perform well with a relatively smaller dataset addresses a significant limitation often encountered in deep learning applications, where large datasets are typically required. The other models that are used for the comparison are k-nearest neighbor (KNN), multilayer perception (MLP), logistic regression (LR), random forest (RF), decision tree (DT), and AdaBoost.

Block-chain for traceability and supply chain transparency in fresh and processed products

Traditional traceability systems often suffer from fragmentation, with data stored in various databases and formats, making it challenging to track produce effectively.



Predictive models for shelf-life estimation in horticultural produce



CNN-XgBoost based ripening identification in banana

Blockchain technology has emerged as a transformative tool for enhancing traceability and transparency in the supply chain, particularly in the postharvest management of horticultural crops. Quality assurance involves ensuring that fruits and vegetables meet safety standards and quality expectations throughout their journey from harvest to consumption. Blockchain facilitates this by creating a transparent and verifiable record of every transaction and condition encountered during the supply chain. For example, as produce is harvested, key data points such as the date, time, and method of harvest can be recorded on the blockchain. Furthermore, the decentralized nature of blockchain enhances trust in the quality assurance process. Each participant in the supply chain—be it farmers, distributors, retailers, or consumers—has access to the same verified information, thereby reducing disputes and fostering greater collaboration. This transparency not only enhances relationships among stakeholders but also empowers consumers to make informed choices about the produce they purchase. Enhancing traceability from farm-to-fork is another critical benefit of blockchain technology in postharvest management. In addition, the integration of blockchain with IoT devices further strengthens traceability efforts. Radio frequency identification technology (RFID) and IoT sensors for tracing the condition of materials during the transportation, and these models are also able to identify the diseases and rotten fruits and bad quality food materials, humidity, and temperature during the process of food supply chain and helps in correctly identifying the target places. IoT sensors can continuously monitor conditions such as temperature, humidity, and gas levels during storage and transportation. This real-time data can be recorded on the blockchain, providing an additional layer of verification regarding the handling conditions of produce. If conditions deviate from optimal ranges, alerts can be generated, allowing for timely interventions to prevent spoilage.

Future trends and emerging technologies

Autonomous robots for harvesting and processing: One of the most promising advancements is the development of autonomous robots for harvesting and postharvest processing. These robots are equipped with advanced sensors and artificial intelligence, enabling them to

perform complex tasks with precision and efficiency. For example, robotic systems can be programmed to identify ripe fruits based on colour, size, and other visual indicators, significantly reducing labour costs and the risk of damage associated with manual harvesting. Furthermore, autonomous robots can operate continuously, allowing for timely harvesting that minimizes losses due to over ripeness or spoilage. In postharvest processing, robots can automate sorting, grading, and packing, which enhances efficiency and consistency while freeing human workers for higher-value tasks.

Use of nano-sensors and quantum computing in monitoring: Nano-sensors, which can detect minute changes in environmental conditions, are being developed to monitor factors such as gas composition, humidity, and temperature at unprecedented levels of sensitivity. These sensors can be embedded in packaging materials or integrated into storage facilities, providing real-time data that can be analyzed for effective decision-making. Meanwhile, quantum computing holds the potential to process complex datasets rapidly, enabling advanced predictive modeling and optimization of postharvest logistics. By harnessing the power of quantum algorithms, stakeholders can simulate and analyze multiple scenarios simultaneously, leading to more effective strategies for minimizing waste and enhancing product quality.

Integration of 5G and edge computing for real-time decision making: The integration of 5G and edge computing technologies is set to revolutionize real-time decision-making in postharvest management. With the advent of 5G networks, the speed and capacity of data transmission will increase dramatically, allowing for seamless communication between IoT devices deployed throughout the supply chain. Edge computing, which involves processing data closer to the source rather than relying solely on centralized data centers, will facilitate real-time analytics and responsiveness. This real-time capability is crucial for maintaining the integrity of perishable products and ensuring that stakeholders can respond proactively to any challenges that arise during transportation and storage.

Digital twin technology: Digital twin technology represents a transformative approach in the field of postharvest management for horticultural crops. At its core, a digital twin is a virtual model that mirrors a physical object or system, utilizing real-time data to simulate, analyze, and optimize its performance. In postharvest management, this technology enhances efficiency, reduces waste, and improves the overall quality of produce during critical stages such as storage and transportation. In addition to real-time monitoring, digital twins harness the power of predictive analytics and ability to optimize processes. This analysis helps identify the most efficient practices, which not only reduces waste but also enhances the overall productivity of the supply chain. Moreover, digital twins can serve as sophisticated decision support systems, providing actionable insights to stakeholders. Digital twins provide actionable data for exporters, retailers, and consumers, such as the remaining shelf-life for each shipment, on which logistics decisions and marketing strategies can be based. The twins also help

diagnose and predict potential problems in supply chains that will reduce food quality and induce food loss. Twins can even suggest preventive shipment-tailored measures to reduce retail and household food losses.

Challenges in the adoption of digital technologies

The adoption of digital technologies for postharvest management of fruits and vegetables presents numerous benefits; however, has several challenges including technological barriers, data privacy concerns, cyber security, high initial costs, skills gaps, and scalability issues. Technological barriers and infrastructure limitations are among the most significant obstacles to the adoption of digital technologies in postharvest management. Limited internet connectivity, inadequate power supply, and lack of access to modern storage facilities can impede the implementation of digital solutions. Stakeholders may also be reluctant to adopt technologies that require sharing data with third parties due to fears of data breaches or misuse. Additionally, as more devices become interconnected, the risk of cyberattacks increases. Cybersecurity vulnerabilities can lead to unauthorized access to sensitive data or disruption of operations, undermining trust among stakeholders. Besides, high initial costs, concerns regarding return on investment (ROI) represent another barrier to widespread adoption. The skills and knowledge gap among stakeholders' poses a significant challenge in the successful implementation of digital technologies in postharvest management. Scalability and interoperability issues also complicate the adoption of digital technologies in the postharvest sector. Many digital solutions are designed as stand-alone systems, making it challenging to integrate them with existing technologies and processes. Furthermore, as businesses grow and operations expand, scaling up digital solutions can be complex and costly.

SUMMARY

The integration of digital technologies in the postharvest management of fruits and vegetables has ushered in a new era of efficiency, quality, and

sustainability within the horticultural supply chain. By leveraging advanced tools such as IoT devices, machine learning algorithms, and blockchain technology, stakeholders can significantly enhance various aspects of postharvest operations. One of the most significant benefits of digital technologies is the enhancement of efficiency and the reduction of losses throughout the postharvest process. With the deployment of IoT devices, real-time monitoring of environmental conditions, such as temperature and humidity, becomes feasible. Advanced quality assessment tools, such as machine learning algorithms and computer vision systems, enable precise grading of fruits and vegetables based on visual attributes like colour, size, and surface defects. Moreover, blockchain technology enhances food safety by providing an immutable record of the product's journey, including details about handling practices and any treatments applied. Advanced analytics platforms allow stakeholders to model and simulate different storage conditions and transportation routes, identifying the optimal parameters for specific types of produce. By utilizing predictive analytics, stakeholders can forecast demand more accurately, allowing for better inventory management. Machine learning models can analyze historical sales data, weather patterns, and market trends to predict the shelf-life of various produce items. By aligning production with actual demand, farmers and distributors can minimize excess supply that leads to waste. Additionally, real-time monitoring systems can detect spoilage at an early stage, enabling quick responses to salvage affected batches or redirect them to processing facilities rather than allowing them to go to waste. The extensive data collected through various digital tools provide valuable insights into consumer preferences, market trends, and product performance.

For further interaction, please write to:

Dr Suresh Kumar P. (Principal Scientist), ICAR-National Research Centre for Banana, Tiruchirappalli, Tamil Nadu 620 102.
*Corresponding author: Suresh.Paramasivam@icar.gov.in

Tractor-operated raised-bed former-cum-planter for multiplier onions

A tractor-operated raised-bed former-cum-multiplier onions. The drive to the metering unit is derived from the ground wheel. A shoe-type furrow opener is fitted to the planting frame in front of onion bulb delivery tube. A funnel-shaped box was also fitted at the bottom of the seed delivery tube to prevent spillage of the onion bulb outside the furrow. This ensures an uninterrupted free-fall of the onion bulb from metering disc to furrow. The furrow opener assembly was mounted independent to the planter unit hence it can be positioned as required to ensure proper row spacing. The effective field capacity of the machine was 0.3 ha/h with field efficiency of 75%.

onion bulb planter has been developed for planting



Source: ICAR Annual Report 2022-23