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Advances in Post-Harvest Engineering and Technology for Sustainable Agro-Processing in India

Fakir Mohan Sahu
Centre of Excellence on Post Harvest Technology, ASPEE College of Horticulture, Navsari Agricultural University, Navsari, Gujarat – 396450, India

**Corresponding author: fmsphtc@nau.in*

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ABSTRACT

Post-harvest losses continue to be a critical bottleneck in the Indian agri-food supply chain, adversely affecting food security, farmers' income, nutritional availability, and sustainability of agro-based industries. Estimates suggest that 15–25% of agricultural and horticultural produce in India is lost annually due to inefficient post-harvest handling, inadequate storage infrastructure, and limited processing capacity. Post-harvest engineering and technology play a pivotal role in addressing these challenges by applying engineering principles to harvesting, handling, drying, storage, processing, packaging, transportation, and quality evaluation of agricultural produce. Over the past decade, significant progress has been made in the development of post-harvest machinery, energy-efficient drying systems, cold-chain infrastructure, non-destructive quality assessment tools, and value-added processing technologies. This review critically examines recent advances (2015–2025) in post-harvest engineering and technology in India, with a focus on mechanization, processing, storage, cold-chain management, packaging, and quality evaluation. The role of national institutions, professional societies, and policy initiatives in promoting post-harvest innovations is highlighted. Key challenges, adoption constraints, and future research priorities are discussed with the aim of strengthening sustainable agro-processing, rural entrepreneurship, and resilience of India's agri-food systems.

Keywords: Post-harvest engineering, agro-processing, mechanization, cold chain, value addition, sustainability

1. INTRODUCTION

India is one of the world's largest producers of agricultural and horticultural commodities; however, a substantial proportion of this production fails to reach consumers due to post-harvest losses. Rapid population growth, changing food consumption patterns, urbanization, and rising demand for quality and safe food have intensified the need for efficient post-harvest systems. Post-harvest engineering encompasses the application of mechanical, thermal, electrical, and material engineering principles

to ensure efficient handling, processing, storage, and distribution of agricultural produce from farm to fork.

During the last decade, the focus of Indian agriculture has gradually shifted from production-centric approaches to value chain-based development. In this context, post-harvest engineering has emerged as a critical discipline for reducing losses, improving shelf life, enhancing value addition, and increasing farmers' income. Institutions under the Indian Council of Agricultural Research (ICAR), state agricultural universities, and professional bodies such as the Indian Society of Agricultural Engineers (ISAE) have made significant contributions in research, technology development, and capacity building. This review presents a comprehensive synthesis of advancements in post-harvest engineering and technology in India during 2015–2025, emphasizing sustainability, affordability, and scalability.

2. Significance of Post-Harvest Engineering in Indian Agriculture

Post-harvest engineering bridges the gap between agricultural production and consumption by ensuring efficient utilization of harvested produce. Its significance lies in multiple dimensions:

- **Reduction of post-harvest losses:** Engineering interventions minimize mechanical damage, physiological deterioration, and microbial spoilage.
- **Enhancement of food quality and safety:** Improved handling, processing, and storage systems help maintain nutritional and sensory attributes.
- **Value addition and income generation:** Processing and product diversification increase market value and create rural employment opportunities.
- **Support to exports and competitiveness:** Standardization, grading, and packaging enable compliance with domestic and international quality standards.
- **Sustainability and resource efficiency:** Energy-efficient technologies and by-product utilization contribute to environmentally sustainable agro-processing.

In India, where small and marginal farmers dominate the agricultural landscape, the development of low-cost, decentralized post-harvest technologies is particularly crucial.

3. Mechanization of Post-Harvest Operations

Mechanization is a cornerstone of post-harvest engineering, transforming labor-intensive traditional practices into efficient and standardized operations. Recent advancements include:

3.1 Primary Processing Machinery

Development of improved threshers, shellers, decorticators, and cleaners for cereals, pulses, and oilseeds has significantly reduced drudgery and processing time. Design optimization focusing on throughput, kernel recovery, energy efficiency, and ergonomics has enhanced machine adoption, particularly in rural and tribal regions.

3.2 Fruit and Vegetable Handling Equipment

Modern graders, sorters, washers, and conveyors have been developed for fruits and vegetables to ensure uniformity and reduce mechanical damage. Optical and sensor-based grading systems are gradually being introduced for high-value commodities.

3.3 Drying Technologies

Drying remains one of the most critical post-harvest operations. Advances in solar dryers, hybrid dryers, and mechanical dryers have improved drying efficiency while reducing dependence on fossil fuels. Improved drying technologies help retain nutritional quality and reduce microbial contamination.

4. Advances in Agro-Processing and Value Addition

Agro-processing adds economic value to raw agricultural produce and extends shelf life. Recent developments include:

4.1 Minimal and Fresh-Cut Processing

Minimal processing technologies such as washing, peeling, cutting, and packaging under controlled conditions have gained popularity due to increasing demand for ready-to-eat and ready-to-cook products.

4.2 Thermal and Non-Thermal Processing

Traditional thermal processing methods such as blanching, pasteurization, and sterilization are being complemented by non-thermal technologies like pulsed electric fields, ultraviolet treatment, and ozone processing to retain quality and nutritional attributes.

4.3 By-Product Utilization

Engineering solutions for utilizing processing waste and by-products into animal feed, bioenergy, and value-added products support waste minimization and circular economy principles.

5. Storage and Cold-Chain Management

Storage is vital for maintaining produce quality and reducing seasonal gluts. Recent innovations include:

5.1 Improved Storage Structures

Scientific warehouses, improved bins, and hermetic storage systems have been developed for cereals and pulses to minimize storage losses.

5.2 Cold Storage and Controlled Atmosphere Systems

Cold storage, controlled atmosphere (CA), and modified atmosphere (MA) technologies have been widely adopted for fruits and vegetables. Emphasis is being placed on energy-efficient refrigeration systems and renewable energy integration.

5.3 Integrated Cold Chain

The development of integrated cold-chain infrastructure from farm to market has improved market access and reduced spoilage of perishable commodities.

6. Packaging Innovations and Material Engineering

Packaging plays a critical role in protection, preservation, convenience, and communication. Recent advancements include:

- Development of biodegradable and eco-friendly packaging materials
- Improved cushioning and protective packaging for long-distance transport
- Active and intelligent packaging systems for quality monitoring

7. Quality Evaluation, Sensors, and Automation in Post-Harvest Agro-Processing

Quality evaluation is a critical component of post-harvest engineering, directly influencing market acceptability, processing efficiency, storage life, and consumer safety of horticultural and agricultural produce. Traditional quality assessment methods in India largely rely on visual inspection, manual sorting, and basic physical or chemical tests, which are often subjective, time-consuming, and prone to human error. In recent years, advances in sensors, instrumentation, and automation have transformed post-harvest quality management systems, enabling rapid, accurate, and non-destructive evaluation of produce.

7.1 Conventional and Instrument-Based Quality Evaluation

Quality attributes of post-harvest produce are broadly categorized into physical, chemical, physiological, and microbiological parameters. Conventional evaluation includes measurement of size, shape, colour, firmness, total soluble solids (TSS), acidity, moisture content, and external defects. Instruments such as refractometers, penetrometers, colorimeters, and moisture meters have long been used to provide objective and repeatable measurements.

However, these methods are often destructive, sample-based, and unsuitable for high-throughput grading lines. The limitations of conventional techniques have driven the adoption of advanced sensing technologies that allow rapid, non-destructive, and real-time quality assessment, especially in large-scale agro-processing and export-oriented supply chains.

7.2 Non-Destructive Sensing Technologies

Non-destructive evaluation (NDE) techniques have emerged as a cornerstone of modern post-harvest quality management. These technologies assess internal and external quality attributes without causing damage to the produce.

Near-Infrared (NIR) spectroscopy is widely used to estimate internal quality parameters such as sugar content, moisture, oil content, and maturity index. NIR-based systems have been successfully applied in fruits like mango, apple, banana, citrus, and pomegranate for rapid grading and maturity assessment.

Hyperspectral and multispectral imaging combine imaging and spectroscopy to capture spatial and spectral information simultaneously. These technologies enable detection of internal defects, bruises, fungal infection, chilling injury, and compositional variations that are not visible to the naked eye. Although highly effective, their adoption in India is currently limited due to high initial cost and technical complexity.

Machine vision systems, based on digital cameras and image processing algorithms, are increasingly used for automated grading based on size, shape, colour, and surface defects. These systems are suitable for integration into conveyor-based grading lines and are particularly relevant for fruits, vegetables, and processed products under PMKSY-supported infrastructure.

7.3 Sensors for Quality, Safety, and Shelf-Life Prediction

Advanced sensors play a vital role in monitoring quality and safety throughout storage, transportation, and processing stages. Electronic nose (e-nose) and electronic tongue (e-tongue) systems mimic human sensory perception and are used to detect aroma compounds, spoilage, fermentation status, and off-flavours in fruits, vegetables, oils, and processed foods.

Gas sensors for oxygen, carbon dioxide, and ethylene are extensively used in controlled atmosphere (CA) and modified atmosphere packaging (MAP) systems to optimize storage conditions and delay ripening. Temperature and humidity sensors, integrated with data loggers and IoT platforms, enable real-time monitoring of cold chain performance and help reduce post-harvest losses.

Biosensors and rapid test kits are gaining importance for detecting pesticide residues, microbial contamination, and chemical adulterants, thereby strengthening food safety compliance and traceability systems.

7.4 Automation, Robotics, and Smart Processing Systems

Automation in post-harvest operations enhances efficiency, consistency, and labour productivity. Automated sorting, grading, washing, waxing, and packaging lines are increasingly being adopted in modern packhouses and processing units. Programmable Logic Controllers (PLCs), Supervisory Control and Data Acquisition (SCADA) systems, and sensor-based feedback mechanisms ensure precise control of processing parameters.

Robotics is an emerging area in post-harvest handling, particularly for repetitive and precision-based operations such as picking, sorting, palletizing, and packaging. Although robotic systems are still at a nascent stage in India, their future adoption is expected to grow with declining costs and increasing labour scarcity.

The integration of Internet of Things (IoT), artificial intelligence (AI), and machine learning (ML) enables predictive quality modeling, automated decision-making, and intelligent grading systems. These smart technologies support traceability, quality forecasting, and supply chain optimization, which are essential for export competitiveness and organized retail markets.

7.5 Indian Context, Challenges, and Future Prospects

Despite significant technological advancements, large-scale adoption of sensors and automation in India faces challenges such as high capital cost, lack of technical expertise, fragmented supply

chains, and limited awareness among small and marginal farmers. However, government initiatives like PMKSY, PMFME, and ODOP provide strong institutional support for establishing modern packhouses, common processing facilities, and technology-driven micro-enterprises.

Future research and development should focus on developing low-cost, robust, and farmer-friendly sensor systems tailored to Indian conditions. Indigenous innovation, capacity building, and public–private partnerships will play a crucial role in scaling up automation and smart quality evaluation systems for sustainable agro-processing.

8. Institutional Support and Government Policy Initiatives

Institutional support and enabling government policies play a decisive role in strengthening post-harvest engineering and agro-processing systems in India. Research institutions under the Indian Council of Agricultural Research (ICAR), particularly the ICAR–Central Institute of Post-Harvest Engineering and Technology (CIPHET), state agricultural universities, and professional bodies such as the Indian Society of Agricultural Engineers (ISAE) have contributed significantly to technology development, validation, and dissemination. In recent years, flagship Government of India initiatives have further accelerated the adoption of post-harvest technologies by providing financial assistance, infrastructure support, and capacity-building mechanisms.

8.1 Pradhan Mantri Kisan Sampada Yojana (PMKSY)

The Pradhan Mantri Kisan Sampada Yojana (PMKSY) is a comprehensive umbrella scheme of the Ministry of Food Processing Industries (MoFPI) aimed at creating modern agro-processing infrastructure and efficient supply chain systems from farm gate to consumer. PMKSY has facilitated the establishment of mega food parks, integrated cold-chain projects, agro-processing clusters, and value addition centers across the country.

Post-harvest engineering interventions supported under PMKSY include grading and sorting units, cold storage facilities, ripening chambers, primary processing lines, and packaging systems. These interventions have contributed to reduction in post-harvest losses, stabilization of market prices, and improved access of farmers to organized markets. The scheme has also encouraged private investment in post-harvest infrastructure, thereby strengthening linkages between farmers, processors, and retailers.

8.2 Pradhan Mantri Formalisation of Micro Food Processing Enterprises (PMFME)

The PMFME scheme focuses on the formalization and strengthening of micro food processing enterprises through credit-linked subsidies, skill development, entrepreneurship training, branding, and market linkage support. The scheme has significantly enhanced the relevance of small-scale and decentralized post-harvest engineering technologies.

Affordable machinery such as mini dryers, pulverizers, oil expellers, decorticators, grinders, and small packaging units play a crucial role in enabling micro-enterprises to operate efficiently. Post-harvest engineering solutions under PMFME are designed to be energy-efficient, easy to operate, and scalable, making them suitable for farmer producer organizations (FPOs), self-help groups (SHGs), and rural entrepreneurs. The scheme has promoted value addition at the local level, thereby increasing farmers' income and generating rural employment.

8.3 One District One Product (ODOP)

The One District One Product (ODOP) initiative aims to promote district-specific agricultural, horticultural, and allied products by strengthening localized value chains. ODOP has created demand for customized post-harvest engineering solutions tailored to specific crops such as fruits, vegetables, spices, cereals, oilseeds, and forest produce.

Engineering interventions related to primary processing, drying, storage, packaging, and quality improvement are central to enhancing product quality and market competitiveness under the ODOP framework. By focusing on localized processing and branding, ODOP supports diversification, reduces transportation losses, and encourages entrepreneurship based on regional strengths.

8.4 Convergence with Post-Harvest Engineering for Sustainable Agro-Processing

The convergence of PMKSY, PMFME, and ODOP with post-harvest engineering research and extension has created significant opportunities for sustainable agro-processing in India. These initiatives collectively promote technology adoption, infrastructure development, skill enhancement, and entrepreneurship.

By integrating engineering innovations with policy support, these schemes strengthen farm-to-market linkages, reduce post-harvest losses, enhance value addition, and contribute to income enhancement and rural employment generation. The synergy between institutional research, government initiatives, and private sector participation is essential for building resilient, inclusive, and sustainable agri-food systems in India.

9. Challenges and Future Research Priorities

Despite significant progress, challenges remain related to affordability, technology adoption, infrastructure gaps, and skill development. Future research priorities include:

- Development of low-cost, farmer-friendly technologies
- Digital and smart post-harvest systems
- Climate-resilient storage and processing solutions
- Strengthening research–industry–farmer linkages

10. CONCLUSION

Post-harvest engineering and technology are pivotal for sustainable agro-processing, food security, and rural livelihoods in India. By applying engineering principles to harvesting, handling, storage, processing, packaging, and quality evaluation, these innovations reduce losses, preserve nutritional quality, and extend shelf life. Advances in mechanization, drying, cold-chain management, packaging, and non-destructive sensing have improved efficiency, consistency, and market competitiveness of agricultural produce. Smart technologies such as IoT-based monitoring, machine vision, and automation are increasingly enabling real-time quality assessment and optimized supply chains. Government initiatives like PMKSY, PMFME, and ODOP, supported by ICAR and state agricultural universities, have accelerated technology adoption, infrastructure development, and entrepreneurship. While challenges remain in affordability, technical skills, and adoption among

smallholders, continued research, low-cost innovations, and public–private collaboration can overcome these barriers. Integrating technology, policy, and capacity building ensures reduced post-harvest losses, enhanced value addition, and resilient, sustainable agri-food systems for India's future.

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