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Modern post-harvest technologies and equipment for improved quality and safety of mango fruits: A review

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Abstract

The mango (*Mangifera indica* L.), along with many other fruit species, is considered one of the most commercially valuable tropical fruit plants. The reasons for such an estimation of mangoes include their high nutritional value, unique taste, and considerable economic contribution to the global fruit industry. However, being a very perishable product and highly vulnerable to the risk of mechanical damage, physiological problems, microorganisms' spoilage, and quality decline, mango requires the application of new post-harvest technologies and equipment to preserve fruit quality, guarantee food safety, prolong shelf-life, and improve efficiency in supply chains. Thus, this literature review gives an overall look at the latest post-harvest technologies and equipment that enhance quality and food safety of mangoes. They include modern harvesting equipment, washers and sanitizers, hot water treatment equipment, hydro-cooling and pre-cooling equipment, mechanical graders and sorters, waxing equipment, ripening rooms, cold storage, CA and MAP, refrigerated transport, as well as non-destructive quality evaluation instruments. In addition, some innovative post-harvest technologies, such as machine vision systems, NIR spectroscopy and hyperspectral imaging, IoT-based monitoring systems, AI technology, automation systems, edible coatings, and sustainable packaging solutions are also included in the review. From the available literature, the use of contemporary post-harvest technologies with modern machinery has been shown to greatly improve the firmness, appearance, nutrition, safety, shelf-life, and acceptability of the fruits while minimizing post-harvest losses and maximizing economic benefits. The future studies need to be directed towards developing cost-effective and energy-efficient post-harvest systems as well as innovative digital technologies for the sustainable management of post-harvest supply chains of mangoes.

Keywords: *Mangifera indica*, post-harvest technology, mango, processing machines, food safety, fruit quality, cold chain, controlled atmosphere storage, machine vision, IoT, artificial intelligence, sustainable post-harvest technology

1. Introduction

Despite high production, mango fruits are highly perishable because of their climacteric nature, characterized by rapid respiration and ethylene production after harvest. These physiological changes accelerate ripening and increase susceptibility to microbial spoilage, mechanical injury, moisture loss, and physiological disorders. It is estimated that post-harvest losses of mango range from 20% to 40% in many developing countries due to inadequate harvesting methods, poor handling, insufficient storage facilities, and inefficient transportation systems. Such losses reduce farmers' income, decrease market availability, and affect export competitiveness. Post-harvest technology has emerged as an essential component of the mango value chain by minimizing quantitative and qualitative losses while maintaining fruit quality and extending shelf life. Modern post-harvest technologies involve scientific harvesting techniques, careful grading and sorting, washing and sanitation, hot water treatment, fungicidal or eco-friendly treatments, edible coatings, controlled atmosphere (CA) storage, modified atmosphere packaging (MAP), cold chain management, and non-destructive quality assessment methods.

These technologies help preserve fruit firmness, color, texture, nutritional composition, and sensory attributes while reducing microbial contamination and physiological deterioration. Mango (*Mangifera indica* L.) is one of the major tropical and sub-tropical fruits crops worldwide, and has been referred to as the "King of Fruits" owing to its good taste, fragrance, nutritive value and economic importance. India is the largest producer of mangoes in the world and produces more than 40% of total world production. Mango production is an important livelihood of many farmers and plays a vital role in the agricultural economy of India through internal consumption, industries and exports. Some popular Indian varieties like Dashehari, Alphonso, Langra, Kesar, Banganapalli and Chausa have high fruit quality and market demand. The use of modern post-harvest equipment has greatly enhanced mango handling processes. Equipment like mechanical harvesters, graders, sorters, fruit washer, hot water treatment machine, hydro-cooler, forced-air cooling system, cold storage, controlled atmosphere storage, ripening chamber, packer and reefer have been used in commercial mango productions. This review is an attempt at thoroughly investigating the technologies and machinery used in the process of post-harvest handling of mangoes. This review focuses on new advances made in the technology used in the process of ensuring the quality of fruits, in food safety, in minimizing post-harvest losses and improving the economic value of mangoes.

2. The Significance of Post-Harvest Management for Mangoes The mango (*Mangifera indica* L.) fruit crop is considered one of the most important crops grown throughout the world because of its rich nutrient content, consumer preference, and economic significance. But mango is a very perishable climacteric fruit crop, which exhibits a rapid rate of physiological and biochemical changes after harvesting. These changes often cause significant post-harvest losses that are associated with poor harvesting practices, mechanical damages, microbial infections, water loss, and inadequate post-harvest handling methods and storage facilities. The post-harvest losses in mango producing nations often account for up to 20% and 40% losses of this fruit crop. Post-harvest management helps to maintain fruit quality, reduce post-harvest losses, and prolong the shelf-life of mangoes. Proper harvesting at appropriate maturity level, handling, de-sapping, washing, sorting, grading, pre-cooling, and packaging are some of the critical practices that help in maintaining the physical, chemical, and sensory qualities of the fruits. Additionally, post-harvest practices can contribute directly to food safety by decreasing micro-organism contamination, reducing pesticide residues via proper handling, and maintaining international standards such as GAP, GMP, HACCP, and ISO 22000 food safety management systems. Such actions will improve consumer trust and create opportunities for domestic and international export markets. In terms of economics, effective post-harvest management will increase profitability of the farming process by reducing quantity and quality losses, improving fruit aesthetics and shelf life, as well as allowing for long-distance transportations. Post-harvest management will be beneficial for value addition via manufacturing of mango pulp, juice, slices, frozen foods, jams, and other products, which means more income and job opportunities. Moreover, sustainable post-harvest

technologies can support environmental protection through energy-efficient cold storages, biodegradable packing material, renewable energy-operated equipment, and use of wastes from mango processing for bioenergy, compost, and value-added products. Such measures can help reduce food losses and improve sustainability of the mango industry. In conclusion, modern post-harvest management has become an essential part of mango production system.

3. Post-Harvest Losses in Mango

Mango is one of the most crucial fruits that belongs to the tropical category, but being climacteric in nature, mango is highly perishable and subject to major post-harvest losses. The harvested fruits keep respiring and ripening very quickly, which makes them vulnerable to physical injury, dehydration, infection, and physiological disorders. The post-harvest losses in many developing nations, including India, are expected to be between 20% and 40% based on the variety of mangoes, methods of handling, storage, transportation, and market conditions. Post-harvest technology and modern equipment are essential in reducing these losses.

3.1 Causes of Qualitative Losses

Qualitative losses involve changes in the physical, nutritional, sensory and market quality of mango fruits without necessarily involving a reduction in quantity. Post-harvest handling problems may cause bruising, discolouration, shriveling, poor colouring and development and hence render the fruits less attractive to consumers. Poor storage conditions lead to an increase in respiration which results in softening and a short shelf life of the products. The nutritional quality of the fruit is also adversely affected by decreased levels of vitamin C, carotenoids, antioxidants and natural fruit flavors as the fruits ripen in storage. Diseases, physiological disorders such as chilling injuries, and contamination of fruits by improper handling procedures will affect the safety of food. The overuse of inappropriate ripening substances such as calcium carbide may result in health hazards as well as affecting fruit quality.

3.2 Economic Impact

The post-harvest loss of mango has economic implications on farmers, traders, food processors, exporters and consumers. Reduction in marketable yields affects the income of the farmer and cost of production per unit of marketed fruits. Poor quality fruits also leads to low prices of the fruits, rejection in export markets and lack of competitiveness internationally.

3.3 Reasons for Quantitative Losses

Quantitative losses can be defined as those where the quantity or weight of mango fruits is reduced through the process of harvest, handling, storing, transporting, and marketing. The causes of quantitative losses are poor harvest techniques, improper handling of mangoes, inappropriate packaging, and poor storage practices. Damage from mechanical injuries such as bruises, cuts, perforations, and compressions cause fruit deterioration and reduce their market value. High rates of respiration and transpiration cause moisture and weight loss. Microbes like fungi such as *Colletotrichum gloeosporioides* (anthracnose)

and Lasiodiplodia the obromae (stem-end rot) cause further decay of the fruits.

Sr, no	P;of Loss	Major Causes	Impact	Modern Technologies to Reduce Losses
1	Qualitative Losses	Bruising, uneven ripening, chilling injury, microbial contamination, nutrient degradation	Poor appearance, reduced shelf life, lower nutritional value, food safety concerns	Optical graders, ethylene ripening chambers, controlled atmosphere storage, modified atmosphere packaging (MAP), edible coatings, quality monitoring sensors
2	Economic Impact	High post-harvest losses and poor quality	Lower farmer income, export rejection, increased food waste, reduced consumer satisfaction	Integrated cold chain, automation, AI-based grading, IoT monitoring, improved packaging and logistics
3	Quantitative Losses	Mechanical injury, moisture loss, fungal decay, insect damage, poor packaging, delayed transport	Reduced fruit weight and marketable yield	Fruit harvesters, plastic crates, pre-cooling units, cold storage, refrigerated transport

4. Modern Post-Harvest Machinery for Mango Industry

Mango industries are gradually relying on modern post-harvest machinery for efficient handling of fruits in order to avoid losses, increase quality, increase shelf-life and enhance food safety. Handling fruits using traditional methods leads to injuries, contamination by pathogens, and quick degradation of fruit quality. Modern machinery ensures that the physical, chemical, and sensory quality of mangoes is maintained and improves efficiency in the entire chain of operations.

- a. **Harvesting Machinery:** Harvesting is one of the first and most important phases in post-harvest operations. The wrong method of harvesting could lead to bruising of the fruit, latex staining and damage to stems leading to poor fruit quality. Modern harvesters include telescopic fruit pickers, harvesting bags, and pole mounted cutters. They allow fruits to be harvested without damaging them and falling on the ground.
- b. **Washing and Cleaning Equipment:** Newly harvested mango fruits may be covered by dust, latex, pesticides, and microorganisms. Washing machinery such as bubble washers, spray washers, rotary drum washers, and brush washers is used to wash fruit without causing mechanical injuries. Some sanitation solutions such as chlorinated water, ozone water, and peracetic acid are used in most washing equipment.
- c. **De-sapping Equipment:** The latex flow in the stem of the fruit causes sap burn, black marks on the peel, and affects the marketability of the fruits. Contemporary de-sapping devices include inclined de-sapping racks, conveyor-belt de-sapping machines, and collection trays where the latex drains from the fruit as soon as the fruit is collected.
- d. **Sorting and Grading Equipment:** Sorting and grading of the fruits are important since they help achieve uniformity in size, weight, color, and quality of the fruits. There are different devices used in the sorting and grading process including roller graders, electronic weigh grader, optical color sorter, and machine vision systems. AI grading devices can detect different defects in the fruits such as bruising, blemishing, diseases and irregular fruits.
- e. **Pre-Cooling Equipment:** The pre-cooling process involves the removal of field heat from the harvested fruits prior to their storage or transport. The typical pre-cooling methods involve forced-air cooling, hydro-cooling, vacuum cooling, and evaporative cooling. Rapid cooling ensures slower respiration, delayed ripening, less moisture loss, and inhibition of microbial

growth, thus extending shelf life and maintaining high quality of the fruit.

- f. **Ripening Equipment:** Ripening of mango commercially is no more done with chemicals like calcium carbide; it is done through controlled ethylene ripening chambers. Modern ripening chambers provide optimum temperature (18-24°C), relative humidity (85-95%), and ethylene concentration in order to guarantee good ripening, beautiful peel color, good taste and better acceptability by consumers. The automated environmental control system keeps track of the conditions for ripening.
- g. **Drying Equipment:** Drying equipment is extensively utilized for preparation of dehydrated mangoes including slice, powder, and many other value-added products. The common technologies are cabinet dryers, tray dryers, tunnel dryers, solar dryers, heat pump dryers, vacuum dryers, microwave-assisted dryers, and freeze dryers. These systems facilitate moisture reduction while maintaining nutritional quality, color, aroma, and texture. The freeze dryer provides best quality but higher investment is needed.
- h. **Equipment for Packaging:** Current packaging equipment provides protection against physical injuries and moisture loss in fruits. Automatic weighers, cartoning machines, shrink wrapping machines, vacuum packaging machines, and Modified Atmosphere Packaging (MAP) machines improve the process of packaging and increase the shelf life of products. Smart packaging technologies, which contain freshness indicators and gas sensors, are being developed and applied for monitoring purposes.
- i. **Storage Equipment:** Right storage equipment becomes crucial for fruit quality maintenance after harvesting. The modern equipment includes cold storage, refrigerated storage warehouse, Controlled Atmosphere (CA) storage, Modified Atmosphere (MA) storage, and ultra-low oxygen storage equipment. They allow regulation of temperature, humidity, oxygen, and carbon dioxide content in order to slow down the processes of ripening and prevent fungal rots.
- j. **Transportation Equipment:** Transportation becomes a crucial stage when post-harvest losses can happen. Refrigerated trucks, insulated containers, reefers, and cold chain technology help in keeping the optimal conditions of storage during the transportation process. Temperature and humidity sensors, GPS tracking and data loggers allow constant control of environment parameters.

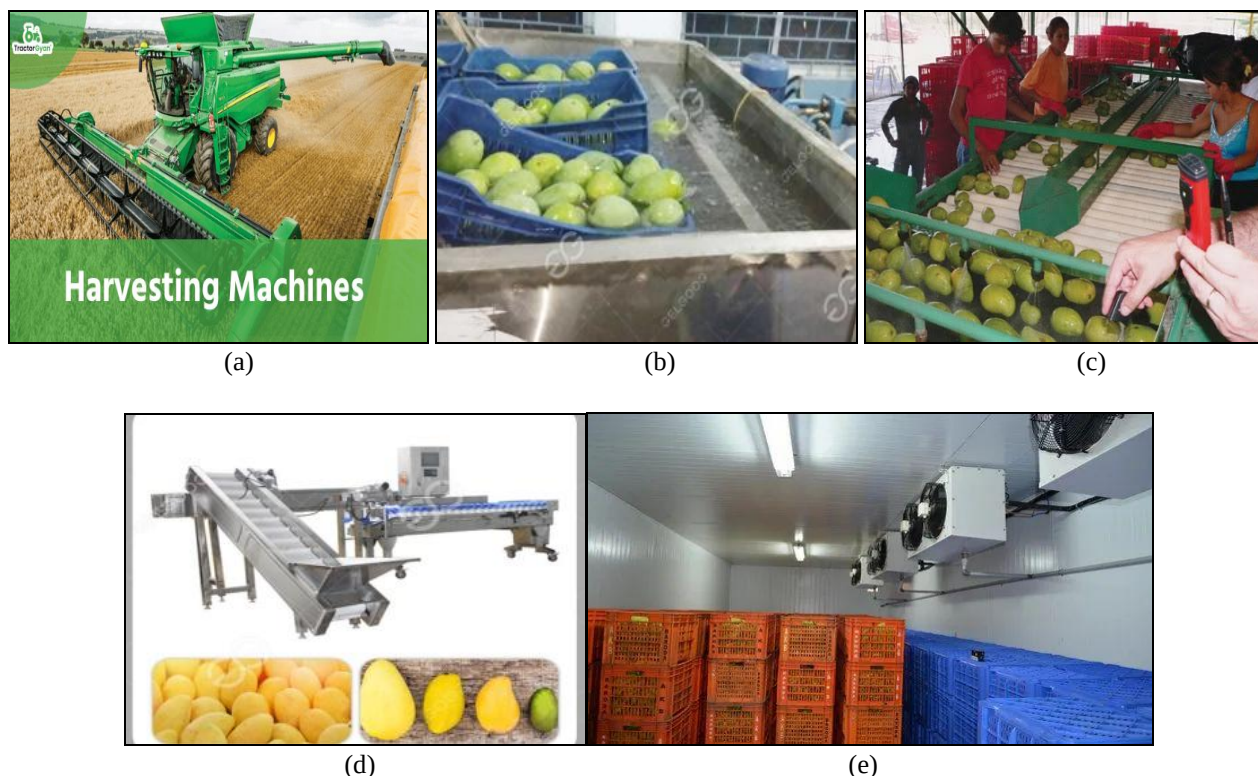


Fig 1: a Harvesting Machinery b. Washing and Cleaning Equipment c. De-sapping Equipment d Sorting and Grading Equipment e. Pre-Cooling Equipment

5. Advanced Post-Harvest Technologies

The technological innovations in post-harvest management have brought a paradigm shift in the mango sector by upgrading the quality of fruits, increasing their shelf life, minimizing post-harvest losses and maintaining the food safety. The conventional methods of post-harvest management are being increasingly substituted by the technologies that include automation, biotechnology, nanotechnology, artificial intelligence (AI), and digital monitoring system. Apart from maintaining the nutritional and sensory quality of mangoes, these technologies make the process highly efficient and cost-effective.

a. Nanotechnology: Nano technology can be used in new ways to develop methods which will help preserve and increase the safety of mango fruits. Nano-coating and nano-emulsion enhance the barrier effects from oxygen, moisture, and microbial contamination. Silver, zinc oxide, titanium dioxide, and nano-clay nanoparticles are used in packaging

materials as inhibitors of bacterial and fungal growth. The sensors that measure temperature, humidity, composition of gases, and microbe activity can be also applied in nanotechnology. However, nanotechnology is still an area requiring further studies related to safety issues, regulatory approval, and environment.

b. Smart Packaging Technologies

Smart packaging is a combination of traditional packaging and sophisticated sensing and monitoring technologies. Smart packaging includes freshness indicators, temperature indicators, humidity sensors, and gas sensors which give current information on fruit quality during storage and shipping. Active packaging is designed to include oxygen absorbers, ethylene absorbers, moisture absorbers, and antimicrobial agents.

Summary of Advancements in Post-Harvest Technologies Applied to Mango

Sr.no	Technology	Working Principle	Main Advantages	Applications
1	Edible coatings	Natural protective coating	Tards fruit from ripening and reduces moisture losses	Fresh mango storage
2	Nanotechnology	Nano-materials and nano-coatings	Microbial protection and smart packaging	Export-grade mangoes
3	Smart Packaging	Sensors and indicators	Quality assessment in real-time	Retail and export markets
4	MAP	Adjusted gas composition	Extends shelf life	Fresh fruits packaging
5	CA storage	Control of oxygen and carbon dioxide	Extends shelf life long-term	Export and commercial warehouses
6	Artificial intelligence	Machine learning algorithm	Automatic mango sorting and defect identification	Packing houses
7	Internet of things (IoT)	Sensor-based monitoring	Systems for real-time storage management	Cold-chain logistics
8	Machine vision	Imaging technologies	Non-destructive fruit quality control	Automated grading lines
9	NIR Spectroscopy	Light absorption techniques	Non-destructive quality evaluation	Research and industry

6. Issues in Adoption of Modern Post-Harvest Technologies

The use of modern post-harvest technologies and machinery has a lot of scope to minimize the losses, enhance the quality of fruit and ensure its safety in the mango industry. But despite all the benefits that modern post-harvest technologies offer, their extensive use still lags behind due to certain economic, technical, infrastructural, institutional, and socio-economic constraints.

- a. **Small and Fragmented Land Holdings:** Mango production in the developing countries like India is dominated by smallholder farmers who cannot afford the purchase of expensive machinery on an individual basis. Collaboration in the use of technology through cooperatives and farmer producer organizations (FPOs) is therefore important.
- b. **High Operational and Maintenance Cost:** High cost of operation and maintenance is another issue which modern post-harvest facilities face due to the constant need to incur expenditures on electricity, fuel, maintenance, replacement, calibration and labor. Increased energy costs raise the operating cost of cold storage and refrigerated transportation facilities.
- c. **Poor Rural Infrastructure:** Limited road infrastructure, unstable electricity supply, poor internet connection, and poor storage capacity create a problem in terms of logistics when trying to keep the quality of the fruits in check during transportation and storage. This lack of infrastructure is especially true for far-off areas where mangoes are cultivated.
- d. **Safety and Quality of Foods:** Export markets are highly regulated with regards to compliance of international food safety and quality guidelines. Such guidelines include GAP, GMP, HACCP, Global G.A.P., and MRLs among others. Most small-scale growers have difficulty meeting these standards because of lack of technical knowledge, costs of certification, and poor monitoring practices.
- e. **Access to Loans and Financing:** Lack of loans to invest in post-harvest infrastructure remains a challenge. The cost of capital and bureaucratic process involved in getting loans make farmers and entrepreneurs unwilling to adopt modern technology.

Conclusion

Mangoes are amongst the most economically valuable tropical fruits; however, their high perishability makes them prone to significant post-harvest losses through harvesting, handling, storage, transportation, and marketing processes. Such losses not only decrease the quantity of marketable fruits but also their nutritional value, sensory attributes, food safety, and commercial value. Modern post-harvest practices and equipment have been found to be an efficient tool for minimizing post-harvest losses without compromising fruit quality. In this paper, the need for implementing modern post-harvest techniques like scientific harvesting, de-sapping, washing and sanitation, pre-cooling, sorting and grading, ethylene ripening in controlled environment, modified atmosphere packaging (MAP), controlled atmosphere (CA) storage, cold chain, and refrigerated transport has been emphasized. Post-harvest practices significantly improve the physical properties,

firmness, colour, flavor, nutritional content, shelf life, and consumer acceptance of fruits while decreasing microbial contamination and post-harvest diseases. Advanced post-harvest technologies include edible coatings, nanotechnology, artificial intelligence (AI), machine vision, hyperspectral imaging, IoT-based monitoring, robotics, cold plasma, UV-C light treatment, ozone technology, and blockchain-based traceability. However, there are a number of impediments that hinder the adoption of these innovations, such as expensive investments, lack of cold chain facilities, inability to get new equipment, scarcity of trained manpower, lack of awareness on the part of farmers, fragmentation of lands, and inadequate financial and institutional support. These hurdles can only be overcome through joint effort on the part of governments, research institutes, extension services, industries, and farmer organizations. Investment in cost-effective post-harvest infrastructure, education of farmers, storage systems using renewable energy sources, information and communication technology, and robust certification of quality standards will help in adopting technology and improving competitive advantage. Future studies need to concentrate on making energy-efficient and environmentally-friendly innovations in post-harvest technology for small scale farming systems. More attention also needs to be paid to quality prediction using artificial intelligence, smart packaging, precision cold chains, biodegradable packaging materials, and digital traceability systems. In general, the proper utilization of contemporary post-harvest technologies and equipment would help in minimizing post-harvest losses, improving quality and safety of fruits, increasing incomes of growers, enhancing export opportunities, and ensuring sustainable development of the mango industry. Further innovations, policies, and cooperation among stakeholders will be necessary for establishing an efficient and resilient post-harvest management system that will be able to cope with the upcoming challenges in the global mango industry.

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