

Freshness That Lasts: Innovative Ways to Preserve Pineapple after Harvest

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Pineapple (*Ananas comosus* L. Merr.) belongs to the family Bromeliaceae and ranks among the most economically important tropical fruits globally. Major producers include Costa Rica, Philippines, Thailand, Indonesia, India and Brazil. In India, pineapple cultivation is concentrated in the Northeastern states along with Kerala, West Bengal, Karnataka and Andhra Pradesh. The fruit plays an important role in the livelihood of farmers and contributes significantly to the tropical fruit economy. The fruit is highly appreciated for its pleasant taste, high juice content, vitamin C, dietary fiber, bromelain enzyme, antioxidants and bioactive compounds. However, despite being a non-climacteric fruit, pineapple is highly perishable after harvest and undergoes rapid quality deterioration during storage and transportation. These losses can range from 20-40% in developing countries where cold chain infrastructure is inadequate. Therefore, the adoption of innovative postharvest technologies is essential to maintain quality, extend shelf life, reduce wastage and improve profitability.

Maturity indices for pineapple harvesting

These indices help growers harvest pineapples at the optimal stage for storage, transport and market requirements. The major maturity indices are -

1. **Skin colour development:** The external peel changes from dark green to light green, yellow-green, and finally golden yellow. Harvest stage depends on market distance, fruits for export are harvested at the mature-green stage, while local markets prefer partially yellow fruits.
2. **Eye flattening:** The individual fruitlets (eyes) become flatter and less prominent as the fruit matures.
3. **Fruit size and shape:** Mature fruits attain characteristic size, cylindrical shape and fullness of the shoulders.
4. **Days after flowering:** Harvest maturity is commonly determined by the number of days after flowering, generally 120-150 days depending on cultivar and growing conditions.

5. **Total soluble solids (TSS):** Mature fruits typically contain 12-16°Brix or higher, indicating adequate sugar accumulation.
6. **Pulp characteristics:** Flesh develops the characteristic yellow colour, aroma and flavour associated with maturity.

Major postharvest problems in pineapple fruits

Pineapple is highly perishable and susceptible to several postharvest problems that reduce fruit quality, shelf life and market value. The major postharvest issues are -

1. **Moisture loss and shrivelling (physiological loss in weight):** Excessive transpiration during storage leads to weight loss, rind shrivelling, and reduced freshness.
2. **Mechanical damage:** Bruising, compression injury, and crown damage occur during harvesting, packaging and transportation, making fruits more prone to decay.
3. **Internal browning (Blackheart):** A physiological disorder characterized by browning of internal tissues without external symptoms, commonly associated with low-temperature storage.
4. **Crown wilting:** The crown loses freshness rapidly due to dehydration and senescence, reducing visual appeal.
5. **Chilling injury:** Storage below 7-10°C can cause peel discoloration, internal browning, water-soaked tissues and poor flavour development.
6. **Microbial decay:** Fungal pathogens such as *Ceratocystis paradoxa*, *Penicillium* spp., and *Fusarium* spp. cause fruit rot and significant postharvest losses.
7. **Over-ripening and senescence:** Rapid metabolic activity results in softening, colour changes, loss of acidity and deterioration of sensory quality.
8. **Crown and stem-end rot:** These diseases develop during storage and transit, especially under high humidity conditions.
9. **Nutritional quality loss:** Prolonged storage can reduce vitamin C content, aroma compounds and overall fruit acceptability.

Pre-cooling: The first step toward preservation of freshness

Field heat accelerates deterioration therefore, pre-cooling is crucial after harvest. Pre-cooling removes excess heat before storage. Different methods of pre-cooling employed are forced air cooling (widely adopted commercially), hydro cooling (rapid heat removal through chilled water), evaporative cooling (suitable for low resource environments), and vacuum cooling (less commonly used for pineapple). Pre-cooling can significantly extend storage life before transportation. Temperature is the most important factor affecting pineapple shelf life. Optimum storage conditions are 7-10°C and relative humidity 85-95%. Under these ideal conditions, fruits can remain marketable for 2-4 weeks. However, Chilling injury is a major limitation as pineapple is sensitive to excessively low temperatures, below 7°C often results in chilling injury. Symptoms are internal browning, water-soaked tissues, poor flavour and increased susceptibility to decay.

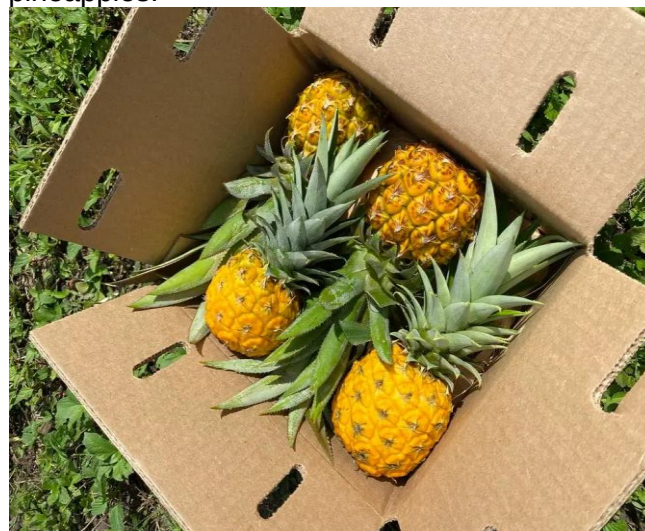
Packaging technologies for pineapple preservation

Packaging technologies play a crucial role in the preservation of pineapple by maintaining postharvest quality and extending shelf life. Techniques such as modified atmosphere packaging (MAP), vacuum packaging, shrink film wrapping and edible coatings are commonly used. These methods regulate gas exchange, reduce respiration rate and minimise moisture loss. MAP adjusts oxygen and carbon dioxide levels to slow ripening and microbial growth, while vacuum packaging limits oxidative reactions. Edible coatings provide biodegradable protective barriers, and shrink films reduce physical damage and contamination. Collectively, these packaging approaches help retain firmness, colour, nutritional quality, and sensory attributes, thereby ensuring improved marketability and reduced postharvest losses.

Corrugated fiberboard box (CFB) packaging

Corrugated fiberboard boxes are extensively used for the packaging and transportation of pineapple fruits due to their strength, lightweight nature and cost-effectiveness. These boxes are constructed from fluted corrugated sheets sandwiched between linerboards, providing excellent cushioning and stacking strength. In pineapple handling, they protect fruits from mechanical damage, compression and vibration during harvesting, storage and long-distance transport. Ventilated designs/perforations facilitate adequate air circulation, reducing heat accumulation and moisture condensation, which helps maintain fruit freshness. The boxes can be combined with

cushioning materials or dividers to prevent abrasion and bruising among fruits. Additionally, corrugated fiberboard is recyclable and biodegradable, making it an environmentally sustainable packaging option compared to plastic alternatives. When used in cold chain systems, these boxes contribute to maintaining optimal temperature and humidity conditions, thereby slowing respiration and ripening processes. Overall, they ensure safe handling, reduced postharvest losses and improved market quality of pineapples.



Modified atmosphere packaging (MAP)

Modified atmosphere packaging (MAP) is an effective postharvest technology used to extend the shelf life and maintain the quality of pineapple. MAP involves altering the composition of gases surrounding the fruit, typically by reducing oxygen levels and increasing carbon dioxide concentrations within a sealed packaging system. This modified gaseous environment slows down the respiration rate and ethylene production, thereby delaying ripening and senescence. In pineapple, MAP helps retain firmness, reduce weight loss and preserve nutritional quality, including vitamin C content. It also inhibits the growth of spoilage microorganisms and reduces enzymatic browning. Common packaging materials used in MAP include semi-permeable polymer films that allow controlled gas exchange, maintaining equilibrium between the fruit and surrounding atmosphere. When integrated with cold storage, MAP significantly enhances postharvest life and marketability. Thus, MAP is a sustainable and efficient approach for minimizing postharvest losses and ensuring high-quality pineapple supply chains.

Active packaging: Unlike conventional packaging, it incorporates functional components such as oxygen scavengers, carbon dioxide emitters/absorbers, ethylene scavengers, moisture regulators and antimicrobial agents.



Intelligent packaging: It incorporates sensing and communication systems that provide real-time information about product condition. Common components include time temperature indicators (TTIs), freshness indicators, gas sensors (for O₂, CO₂, and ethylene) and QR or RFID-based tracking systems. It monitors temperature, humidity and quality changes.

Shrink film wrapping

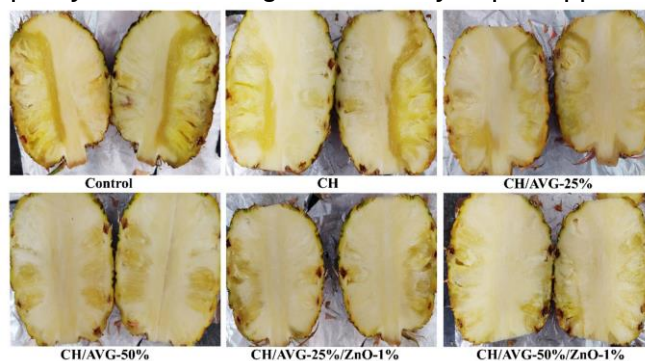


Shrink film wrapping is a widely used postharvest technology for improving the shelf life and quality of pineapple. In this method, heat-sensitive polymer films such as polyethylene or polyvinyl chloride are tightly wrapped around the fruit and then exposed to heat, causing the film to shrink and conform closely to the surface. This creates a modified atmosphere around the pineapple by

reducing oxygen influx and limiting carbon dioxide loss, thereby slowing respiration and metabolic activity. As a result, physiological processes such as ripening, softening and senescence are delayed. Shrink wrapping also minimizes moisture loss, reducing weight reduction and surface dehydration. Additionally, it provides a physical barrier against microbial contamination, mechanical damage, and external contamination during handling and transport. Studies show that shrink film-wrapped pineapples retain better firmness, colour and sensory quality during storage compared to unwrapped fruits. Thus, it is an effective, low-cost preservation technique for extending marketability.

Edible coatings a sustainable preservation strategy

Edible coatings are emerging as a sustainable postharvest preservation strategy for extending the shelf life and maintaining the quality of pineapple fruits. These thin semi-permeable barriers, consumable layers are applied directly onto the fruit surface and act as semi-permeable barriers to gases and moisture. Common coating materials include polysaccharides (chitosan, alginate, starch), proteins (gelatin, whey protein), guar gum, aloe vera gel, carboxy methyl cellulose and lipids, often incorporated with natural antimicrobials or antioxidants. In pineapple, edible coatings help reduce weight loss, slow respiration rate and delay enzymatic browning and microbial spoilage. Chitosan based coatings are particularly effective due to their antimicrobial properties and ability to form uniform films. By modifying internal gas exchange, coatings maintain firmness, titratable acidity and vitamin C content during storage. Additionally, they reduce dependence on synthetic preservatives and plastic packaging, aligning with eco-friendly food preservation goals. Overall, edible coatings offer a biodegradable, safe and cost-effective approach to improving postharvest quality and extending marketability of pineapples.



Chitosan based antimicrobial coating

GRAS treatments for shelf-life enhancement

Generally recognized as safe compounds (GRAS) are increasingly used in postharvest management of fruits. These commonly include calcium

chloride, potassium sorbate, sodium bicarbonate, citric acid and ascorbic acid. GRAS treatments are extensively used to extend the postharvest shelf life of pineapple by minimizing microbial spoilage, physiological weight loss and enzymatic browning while preserving sensory quality. Calcium chloride and other calcium salt dips enhance firmness by cross-linking pectic substances in the cell wall, thereby delaying tissue softening. Anti-browning agents including ascorbic acid, citric acid and calcium ascorbate inhibit polyphenol oxidase activity and maintain fresh-cut colour quality. GRAS-approved antimicrobials such as nisin, natamycin, lactic acid and acetic acid effectively suppress bacterial and fungal growth. Plant-derived essential oils like clove, cinnamon, and lemongrass, often applied in nano emulsion form, provide additional antimicrobial and antioxidant protection. These treatments are commonly integrated with complementary technologies such as modified atmosphere packaging (MAP), refrigeration, UV-C irradiation and mild hot water dips to achieve synergistic preservation effects. Collectively, GRAS-based postharvest interventions significantly enhance pineapple shelf life while maintaining nutritional value, texture and consumer acceptability during storage and distribution. Combining GRAS dips with edible coatings often produces synergistic benefits.

Biological approaches to postharvest disease control

Biological approaches for postharvest disease control in pineapple involve the use of beneficial microorganisms to suppress spoilage pathogens and extend shelf life. These biocontrol agents include antagonistic yeasts (suppress fungal pathogens through competition; *Botrytis cinerea*, *Penicillium* spp., *Rhizopus stolonifer*, *Colletotrichum* spp., *Monilinia fructicola*, *Alternaria alternata* and *Aspergillus niger*), beneficial bacteria (produce antimicrobial compounds; *Bacillus subtilis*, *B. amyloliquefaciens*, *B. pumilus*, *Pseudomonas fluorescens*, *P. putida*), plant extracts (neem extract, cinnamon oil, clove oil, lemongrass oil). They act as natural competitors on fruit surfaces and reduce infection by postharvest fungi. The main mechanisms of action include competition for nutrients and space, production of antimicrobial compounds, secretion of hydrolytic enzymes and induction of host defence responses in pineapple tissues. Some microorganisms also form protective biofilms that prevent pathogen attachment and growth. In pineapple, biological control can be applied through dipping, spraying, or integration with edible coatings and cold storage. These methods are effective against major pathogens responsible for fruit rots and decay. Overall, biological

approaches provide a safe, eco-friendly and residue-free alternative to chemical fungicides, helping to maintain fruit quality and reduce postharvest losses in pineapple.

Cold chain management

Cold chain management is a critical postharvest system used to maintain the quality, safety and shelf life of pineapple fruits from harvest to consumption. It involves a continuous temperature-controlled supply chain that includes precooling, refrigerated storage, cold transport and chilled retail display. Pineapple, being a non-climacteric tropical fruit, is highly sensitive to temperature fluctuations and improper handling can lead to rapid quality deterioration. Immediately after harvest, pineapples are subjected to precooling to remove field heat and slow down respiration and enzymatic activity. The fruits are then stored and transported at optimal low temperatures, typically between 7-13°C, depending on cultivar and maturity stage. Maintaining appropriate relative humidity (85-95%) is also essential to reduce moisture loss and prevent shrivelling. Cold chain management helps minimize microbial growth, delay senescence, preserve firmness and retain nutritional and sensory qualities such as flavour, colour and aroma. Breaks in the cold chain can accelerate spoilage and significantly reduce market value. Integration of technologies such as temperature data loggers, IoT based (internet of things) monitoring systems and smart packaging further enhances cold chain efficiency. Overall, effective cold chain management is essential for reducing postharvest losses and ensuring high-quality pineapple reaches both domestic and international markets. An uninterrupted cold chain is essential for preserving pineapple quality and cold-chain integration is particularly important for long distance marketing.

Minimal processing and fresh cut pineapple preservation

Minimal processing of pineapple refers to the preparation of fresh cut or ready-to-eat pineapple products with minimal alteration from the whole fruit while maintaining fresh like quality. This process typically involves peeling, coring, slicing and packaging under hygienic and controlled conditions. Fresh cut pineapple is highly perishable due to increased respiration rate, enzymatic browning, microbial contamination and tissue damage caused during cutting. To preserve quality, several preservation strategies are applied which include sanitation treatments such as chlorine or organic acid washes, application of edible coatings (chitosan, aloe vera gel or alginate based films), and use of natural antimicrobials like essential oils. Cold storage at low temperatures (0-

5°C) is critical to slow microbial growth and enzymatic reactions. Modified atmosphere packaging (MAP) is also widely used to regulate oxygen and carbon dioxide levels, thereby reducing respiration rate and delaying senescence. Additionally, non-thermal technologies such as UV-C irradiation and ozone treatment may be integrated to enhance microbial safety. These combined approaches help maintain colour, texture, flavour and nutritional quality of fresh cut pineapple. Overall, minimal processing techniques aim to provide convenient, safe and high-quality pineapple products while extending shelf life and reducing postharvest losses in the fresh cut fruit industry.



Emerging technologies in pineapple postharvest management

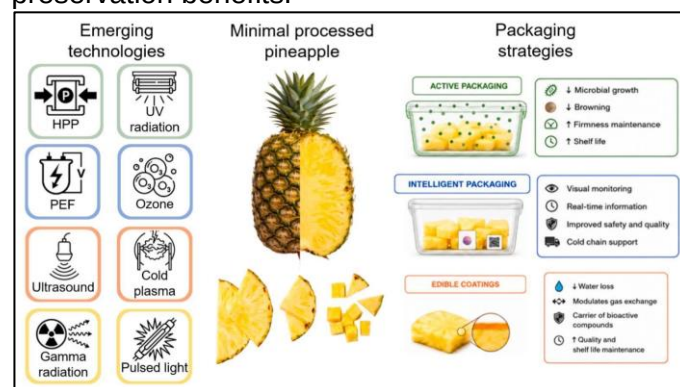
Nanotechnology based coating

Nanotechnology based coatings have emerged as an effective postharvest technology for extending the shelf life and preserving the quality of pineapple fruits. These coatings are formulated using edible biopolymers such as chitosan, alginate or starch incorporated with nanoparticles including nano-chitosan, nano-silver, nano-zinc oxide and nano-cellulose. The nanoscale particles enhance the mechanical strength, barrier properties and antimicrobial activity of the coating. When applied to pineapple surfaces, nano-coatings create a semipermeable film that reduces moisture loss, respiration rate and oxidative deterioration. They also inhibit the growth of spoilage microorganisms and postharvest pathogens, thereby minimizing decay and maintaining fruit firmness, colour, flavour and nutritional quality. Chitosan nanoparticles are particularly effective due to their biodegradability, biocompatibility and broad-spectrum antimicrobial properties. The application of nanotechnology-based coatings offers an eco-friendly alternative to chemical preservatives, reducing postharvest

losses and improving the storage, transportation and marketability of pineapple fruits.

Ozone treatment

Ozone (O_3) treatment is an innovative and environmentally friendly technology used in the postharvest management of pineapple. Ozone is a strong oxidizing agent with broad-spectrum antimicrobial activity against bacteria, fungi, yeasts and viruses. It can be applied in gaseous or aqueous form to sanitize pineapple fruits during storage and transportation. The treatment reduces microbial load on the fruit surface, thereby minimizing postharvest decay and extending shelf life. Ozone also helps maintain fruit quality by reducing respiration rate, delaying senescence and preserving firmness, colour and nutritional attributes. Unlike conventional chemical disinfectants, ozone decomposes rapidly into oxygen without leaving harmful residues, making it a safe and eco-friendly alternative. Studies have demonstrated that appropriate ozone concentrations effectively control postharvest pathogens and reduce spoilage in pineapples. However, excessive exposure may cause oxidative damage to fruit tissues. Therefore, optimizing ozone concentration and treatment duration is essential for achieving maximum preservation benefits.



Ultraviolet C (UV-C) irradiation

Ultraviolet-C (UV-C) irradiation is a non-thermal postharvest technology used to enhance the storage life and quality of pineapple fruits. UV-C radiation, typically at a wavelength of 200-280 nm, possesses strong germicidal properties that effectively inactivate bacteria, fungi and other spoilage microorganisms present on the fruit surface. The treatment damages microbial DNA, preventing replication and reducing postharvest decay. In pineapple, UV-C irradiation has been shown to delay senescence, reduce respiration rate and maintain fruit firmness, colour and nutritional quality during storage. Additionally, UV-C can stimulate the fruit's natural defence mechanisms by inducing the synthesis of antioxidant compounds and defence related enzymes. This process enhances resistance

against postharvest pathogens and oxidative stress. As a residue free and environmentally friendly technology, UV-C irradiation offers an alternative to chemical fungicides. However, appropriate dosage and exposure time are crucial, as excessive irradiation may cause surface injury and quality deterioration.

Cold plasma technology

Cold plasma technology is an emerging non-thermal postharvest treatment used to improve the safety, quality and shelf life of pineapple fruits. Cold plasma is generated by ionizing gases such as air, oxygen or nitrogen at low temperatures, producing reactive oxygen and nitrogen species with strong antimicrobial properties. These reactive species effectively inactivate bacteria, fungi, yeasts and other spoilage microorganisms present on the fruit surface without causing significant heat damage. In pineapple, cold plasma treatment helps reduce postharvest decay, maintain firmness and preserve sensory and nutritional attributes during storage. The technology also delays ripening by reducing respiration rates and microbial activity. Additionally, cold plasma can induce defence responses in fruit tissues, enhancing resistance to postharvest pathogens. As a chemical-free and environmentally sustainable technology, cold plasma leaves no harmful residues and requires minimal water usage. However, treatment parameters such as exposure time, gas composition and power intensity must be optimized to avoid adverse effects on fruit quality.

Smart sensors and IoT

Smart sensors and the Internet of Things (IoT) are increasingly applied in pineapple postharvest management to monitor and maintain fruit quality throughout the supply chain. IoT enabled sensor systems collect real time data on critical parameters such as temperature, relative humidity, ethylene concentration and storage atmosphere composition during storage and transportation. These sensors are integrated with wireless communication networks to transmit data to centralized platforms for continuous monitoring and analysis. In pineapple supply chains, smart sensors help detect early signs of spoilage by tracking physiological changes associated with ripening and microbial activity. This enables timely intervention, reducing postharvest losses and improving decision-making regarding storage conditions and distribution. Additionally, IoT systems support predictive analytics and automated control of cold storage environments, ensuring optimal conditions for extending shelf life. The integration of smart sensing and IoT technologies enhances traceability, efficiency and quality assurance, making pineapple logistics

more sustainable, data-driven and responsive to market demands.

Future perspective

Future research should focus on biodegradable packaging materials, integrated coating and packaging systems, nanotechnology enabled preservation, smart cold chain systems, biological disease management, sustainable postharvest interventions for smallholder farmers and climate resilient storage technologies.

Conclusion

Maintaining pineapple freshness after harvest requires a comprehensive and integrated approach encompassing proper harvesting, sorting, pre-cooling, storage, packaging, disease management and cold-chain maintenance. Innovative technologies such as edible coatings, GRAS dips, shrink-film wrapping, modified atmosphere packaging, biological treatments and smart monitoring systems offers significant opportunities to reduce postharvest losses and extend shelf life. Adoption of these technologies can enhance profitability, improve food security and promote sustainable horticultural development. As consumer demand for high-quality fresh produce continues to grow, innovative postharvest management practices will play an increasingly important role in ensuring that pineapple freshness truly lasts from farm to fork.

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