CIAE/APPD/TB/2025/406

Technologies for Handling and Shelf Life Enhancement of Fresh Commodities

S. Mangaraj

Adinath Kate

M. K. Tripathi

Dilip Pawar

Agro Produce Processing Division
ICAR-Central Institute of Agricultural Engineering
NabiBagh, Berasia Road, Bhopal – 462 038

CIAE/APPD/TB/2025/406

Technologies for Handling and Shelf Life Enhancement of Fresh Commodities

S. Mangaraj

Adinath Kate

M. K. Tripathi

Dilip Pawar

Agro Produce Processing Division
ICAR-Central Institute of Agricultural Engineering
NabiBagh, Berasia Road, Bhopal – 462 038

भाकृअनुप
ICAR

PREFACE

India, is a diverse country with various agro-climatic conditions, and henceenrich with a vast potential for horticultural production, contributing significantly to the global fruit and vegetable production. In recent years, the country has achieved record levels of horticultural production, surpassing 367 million tonnes. However, this remarkable growth is consistently undermined by substantial post-harvest losses, ranging between 6–18% depending on the commodity, amounting to an annual economic loss of over Rs. 1.5 trillion. Such losses are attributed to multiple factors, including inadequate handling practices, cold chain infrastructure, limited on-farm storage facilities, insufficient processing capacity and inadequate farmer awareness. These challenges highlight the urgent need for systematic interventions in post-harvest management with a special focus on shelf life enhancement of fresh commodities.

Shelf life enhancement of fresh agro-commodities has also one of the key priority area of research, policy, and practice. The Hon'ble Minister of Agriculture and Farmers Welfare, Government of India, has also emphasized the critical role of shelf life enhancement of fresh agro commodities in realizing the vision of Viksit Krishi in the proceedings of Viksit Krishi Sankalp Abhiyan (VKSA)-Insights and Outcomes. The importance of this priority area also endorsed by the DG, ICAR and inculcated it in his vision on demand driven research leading to farmer's welfare.In this context, the present document has been prepared to consolidate scientific knowledge, available technologies, and practices that contribute towards extending the shelf life of fresh produce.

The document comprehensively covers a wide spectrum of approaches—ranging from maturity assessment, pre-cooling, washing, advanced preservation technologies, on-farm storage systems, cool and cold storage systems, irradiation, innovative packaging solutions such as modified atmosphere packaging, active and intelligent packaging. In addition, it highlights the possible chemical dip techniques, preservation methods keeping in view of addressing the diverse needs of stakeholders from smallholder farmers to agri-business enterprises.

This compilation is intended to serve as a practical guide for farmers, researchers, policymakers, industry professionals, start-ups and entrepreneurs engaged in the horticultural value chain. By adopting these technologies, India can not only reduce post-harvest losses but also played catalytic role to enhance farmers' incomes, strengthen the food processing sector, and improve the availability of safe, nutritious, and high-quality produce to consumers.

It is our sincere hope that this document will stimulate large-scale adoption of shelf-life enhancement technologiesincludingfurther research and innovation, thereby contributing to the national vision of doubling farmers' income and ensuring sustainable agricultural development.

S. Mangaraj
Adinath Kate
M.K. Tripathi
Dilip Pawar

Importance of shelf life enhancement of fresh commodities

During the year 2024–25, India achieved a record horticulture production of approximately 367.72 million tonnes, reflecting a 1.36 % increase in fruit production and a 6 % rise in vegetables production. However, this enhanced production comes with a significant post-harvest losses remain substantial. Fruits and vegetables collectively losing between 6% to 18% of their volume, depending on the commodity. In 2020-2022 NABCONS (NABARD Consultancy Services) study estimated total post-harvest losses for 54 crops at Rs. 1.5 trillion annually. These substantial financial losses are attributed to factors like a poor cold chain infrastructure, non-availability of farmers friendly on-farm storage systems, lack of processing facilities, inadequate handling and transportation, market volatility and farmer awareness, leading to significant loss of the produce. Shelf-life enhancement of fresh commodities in India holds immense importance due to the country's diverse agricultural base, high production of fruits and vegetables, and significant post-harvest losses. Extending shelf life through improved post-harvest handling, pre-cooling, cold storage, packaging, and advanced preservation technologies not only reduces these losses but also ensures better price realization for farmers, steady supply to markets, and availability of quality produce to consumers. Moreover, enhancing shelf life is crucial for promoting exports, meeting food security challenges, and supporting the rapidly growing food processing sector in India. By adopting modern techniques for shelf-life extension, the country can significantly improve agricultural sustainability, farmer income, and nutritional availability for its vast population. The importance of the shelf life enhancement problem and its national priority of the issue also highlighted during the review meeting of the Hon'ble Minister of Agriculture and Farmers Welfare, Gov. of India, on the Viksit Krishi Sankalp Abhiyan (VKSA) at NASC complex in New Delhi in the presence of Hon'ble Secretary DARE and DG, ICAR and other dignitaries. The importance is also highlighted in the proceedings of Viksit Krishi Sankalp Abhiyan (VKSA)-Insights and outcomes Further, the Hon'ble Agriculture Minister, categorically emphasized on the significance of the Food processing sector and especially appealed to work on the Shelf life enhancement techniques for fresh horticultural commodities. The importance of this issue is also evident from target and dream of the DG, ICAR towards performing demand driven research leading to farmers welfare which is a challenge to the scientists and academicians working in the post-harvest sector. This document would help in identifying the technologies for shelf life enhancement of fresh produce for farmer's, industry personals and road map for future research.

Maturity Assessment and Harvesting

Maturity assessment and harvesting of fruits and vegetables are critical steps in post harvest management to ensure high quality, extended shelf life, and consumer acceptability. Maturity refers to the stage of development when a fruit or vegetable has reached the proper physiological state for harvest, which may be either horticultural maturity (when produce is suitable for consumption) or physiological maturity (when it has completed natural development). Accurate maturity assessment is done using physical, chemical, and sensory indicators such as size, shape, skin color, firmness, total soluble solids, titratable acidity, and aroma. Tools like penetrometers, refractometers, and color charts are commonly used for objective evaluation. Harvesting at the right maturity stage is essential, as immature produce may lack flavor and fail to ripen properly, while overripe produce is prone to mechanical damage, microbial spoilage, and reduced marketability. Proper harvestingpractices, includinguseof suitabletools,minimalhandling,andharvestingduring cooler parts of the day, help reduce mechanical injuries and maintain freshness. Thus, scientific maturity assessment coupled with careful harvesting techniques ensures better quality, reduces postharvest losses, and enhances the value of fruits and vegetables in the supply chain.

- **Harvesting**

Harvesting of fruits and vegetables is a crucial post-harvest operation that directly influences the quality, market value, and shelf life of the produce. It involves the careful selective removal of mature produce from the plant while minimizing mechanical injury and physiological stress. The stage of harvest is determined based on maturity indices, which may include physical indicators, physiological characteristics, and sometimes biochemical parameters. Harvesting at the right stage is vital—premature harvesting can result in poor flavor, shriveling, and reduced nutritive value, while delayed harvesting often leads to over-ripeness, spoilage, and loss during handling and transport.

Manual Harvesting

This is the most common and widely practiced method in India.

- Hand picking:This is the highly practiced method in Indian agriculture for most of the fruits and vegetables. The method is practiced for fruits like tomato, mango, guava, grapes and vegetables like okra, beans, leafy vegetables, pumpkins, guards etc. During harvesting workers carefully detach produce by hand to avoid bruising and hence causes minimum injury during harvesting.
- Clipping/cutting with tools: Some specialized hand tools available in this group are mainly used by some farmers mainly to reduce the drudgery involve in laborious manual operation. The tools like Knives, scissors, or clippers are used for the harvesting of crops like grapes, pomegranates, brinjal, capsicum, and cucumbers. This method reduces mechanical injury and ensures clean cuts at the branch helps for next fruiting and branching.
- Pulling or twisting: For some specialized fruits like citrus, apples, custard apple harvested through gentle twisting which detaches the fruit without damaging the pedicel which helps for minimum moisture loss and maintain the shelf life.

Mechanical Harvesting

This method involves the use of some crop specific machines and tools to harvest produce.

- Harvesters and diggers: The underground crops like potatoes, onions, carrots, and other underground crops are lifted by diggers or conveyor-type harvesters. These machines are mainly tractor operated and some self-propelled machines are also available.
- Shakers and pickers: The specialized tools in this group are used for harvesting of mainly fruit crops like grapes, ber, anola, cherries, jamuns. The machine/tools shakes the tree/vine branches to detach the fruits.
- Cutting machines: Leafy vegetables like spinach, lettuce, cabbage etc. mainly at large fields are harvested using crop specific cutting equipment's.

Transportation

Transportation of fruits and vegetables from the farm gate to the market is one of the most critical links in the post-harvest supply chain in India. Since fruits and vegetables are highly perishable, poor handling and inefficient transport systems often lead to significant losses before the produce even reaches consumers. Transportation of fruits and vegetables by Indian farmers up to mandis is still largely traditional and fragmented, dominated by bullock carts, tractors, and open trucks. The various methods using by the farmers includes:

- **Transportation Using Gunny Bags**

Traditionally, jute or polypropylene gunny bags and wet cotton bags are widely used for transportation of crops like all leafy vegetables, brinjal, chilli, bottle guard, beans etc.The sufficient amount of water is spread over the filled bags keeping in view maintaining the wetness of bags and hence maintaining the freshness of filled material. Because of keeping one above others the overloading causes mechanical damage to the produce and also affect the freshness and quality.

- **Transportation in open bulk**

Some fruits and vegetables are transportation in the form of bulk filling in the transport containers of trucks, trolley, tempo, railway vagons etc. The commodities produced in huge bulk and having slightly higher shelf life are transported using this method. The fruits like citrus, mango, lemons, water melons, papaya, pine apple etc. and vegetables like onion, garlic, potatoes etc. are transported using this method. Farmers prefer this method because it is quick, inexpensive, and suitable for moving large quantities over medium to long distances from rural areas to mandis or wholesale markets. However, the absence of protective packaging and bulk loading leaves the produce highly vulnerable to mechanical injuries such as bruising, compression, and tearing.

- **Transportation in boxes**

Transportation of fruits and vegetables by Indian farmers in boxes is a relatively improved practice compared to traditional bulk loading or gunny bags, particularly for high-value and delicate commodities. Boxes are generally made of corrugated fiber-board (cardboard), wooden planks, thermocol or PET packets and are used for crops such as apple, banana, grapes, pomegranate, litchi, strawberry, custard apple, capsicum etc. Farmers or traders pack the harvested produce in boxes—often with cushioning materials like paper, straw, or foam nets etc. to protect it from bruising and vibration during handling and transit. These boxes are then stacked in tempos, trucks, or lorries and transported to nearby mandis or distant urban markets. Compared to open bulk transport, boxes offer better protection from mechanical injury, dust, rain, and temperature fluctuations, ensuring that fruits and vegetables retain their freshness and visual appeal.

- **Transportation in crates**

Transportation of fruits and vegetables by Indian farmers using plastic crates has become a modern and efficient alternative to traditional methods like gunny bags. Plastic crates, generally made of durable high-density polyethylene (HDPE), are strong, stackable, and ventilated, which helps in maintaining the quality of highly perishable commodities during transit. This is used for delicate commodities like grapes, tomatoes, cherries and leafy greens reach markets in good condition. Farmers place freshly harvested produce directly into crates at the field level, reducing excessive handling and minimizing mechanical injuries such as bruising, crushing, and cuts that are common when gunny bags are used. During transportation from farms to mandis, these crates allow proper air circulation, which prevents heat build-up and delays spoilage, thereby enhancing shelf life. The rigid structure of crates quite easy to accommodate in transport trucks and tractors.

- **Transportation in railway wagons**

Transportation of fruits and vegetables by Indian farmers in railway wagons is mainly used for moving bulk produce over long distances, especially from major production belts to consumption centers. Farmers, traders, and aggregators often use railway wagons to transport crops like potatoes, onions, bananas, mangoes, apples, and other seasonal fruits and vegetables in large quantities to wholesale markets in metropolitan cities. Traditionally, produce is loaded in gunny bags, bamboo baskets, or loose bulk into covered wagons, while in recent years, specialized refrigerated wagons under the “Kisan Rail” scheme have also been introduced to minimize spoilage. Rail transport offers distinct advantages such as lower cost per unit weight, high load-carrying capacity, and faster delivery over long distances compared to road transport. This mode of transport also promoted by government through initiatives such as Kisan Rail and Krishi Udaan, which aim to connect farmers with distant markets efficiently.

- **Refrigerated transport services**

These services focus on maintaining a consistent cold chain for fresh produce during transit within the country and abroad. For exporting fruits and vegetables from India, refrigerated transport services are essential, provided by logistics companies and offered through platforms like IndiaMART and Tradeindia that utilize various refrigerated vehicles, including specialized vans and containers. Key considerations include ensuring the vehicle has advanced temperature control, real-time monitoring capabilities, and operates within a strict hygienic environment to preserve quality and prevent spoilage. For large-scale, intercontinental exports, refrigerated container ships are the primary and most cost-effective method for shipping vast quantities of goods.

Key Components & Services

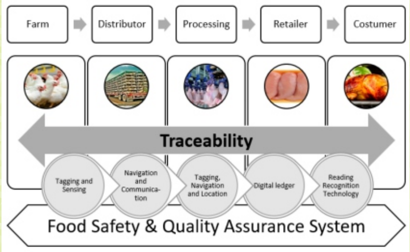
- Refrigerated Vehicles: This includes refrigerated vans, trucks, and containers designed to carry perishable goods at controlled temperatures.
- Insulated Containers: Advanced insulation, often using materials like GRP (glass-reinforced plastic) and RPUF (rigid polyurethane foam), is critical for maintaining temperature and energy efficiency.
- Advanced Refrigeration Systems: These systems are essential for providing precise temperature control and preserving the freshness of fruits and vegetables.
- Cold Chain Logistics: A comprehensive approach to maintaining a continuous supply of refrigerated products in a controlled environment, from production to the final consumer.

For International Exports

Container Shipping: For large-volume exports across seas and oceans, container ships equipped with refrigerated containers (reefer containers) are the most efficient and cost-effective option.

Cold-X Solutions: Brands and logistics providers like RINAC are developing innovative solutions, such as their ChillKart system, for secondary and last-mile transport, making the entire cold chain more efficient for perishable exports.

- **Block-chain Technology**



Block-chain technology provides a secure, transparent, and immutable ledger to track fruits and vegetables throughout the transport supply chain, enhancing food safety, reducing fraud, and increasing consumer trust. It achieves this by combining with IoT sensors to record environmental conditions and product handling data from farm to consumer, using smart contracts to automate processes and ensure regulatory compliance. While challenges exist, the integration of block-chain and IoT offers significant benefits, including real-time monitoring, faster recalls in case of contamination, and greater visibility for all stakeholders.

Working Principle

- Data Collection: IoT sensors (like those used in NFC technology) collect data on the produce's origin, cultivation conditions, and transit environment (temperature, humidity).
- Immutable Records: This data is securely recorded and time stamped on a distributed, unchangeable block chain ledger.

Transparency: All authorized participants in the supply chain, from farmers to consumers, can access this shared ledger, providing end-to-end traceability.

Smart Contracts: These self-executing contracts on the block chain can automate processes, such as payments or compliance checks, based on predefined conditions being met during transport.

Key Benefits

- Enhanced Food Safety: Enables quick identification and tracking of contaminated products, allowing for targeted recalls and reducing the spread of food borne illness.
- Reduced Food Fraud: The tamper-proof nature of block chain records helps prevent counterfeiting and dilution of produce.
- Improved Quality: Real-time monitoring of storage and transport conditions helps preserve the quality of perishable items and reduces spoilage.
- Greater Consumer Trust: Provides consumers with verifiable information about the origin and journey of their food, fostering confidence in product quality and ethical sourcing.
- Operational Efficiency: Streamlines supply chain processes, balances supply and demand, and reduces the costs associated with communication and trust between parties.

Challenges and Considerations

- Integration Complexity: Incorporating block-chain architecture and integrating it with existing systems can be complex.
- Reliance on IoT: The effectiveness of the system depends on the reliability of IoT devices for data collection.
- Technological Maturity: Some aspects, such as immature preservation technology for fruits and vegetables, need further development.
- Commercial Implementation: Transitioning from pilot projects to widespread commercial adoption requires overcoming hurdles in business reconstruction, personnel training, and system maintenance.

- ## Precooling

Precooling is a critical step for removing field heat from freshly harvested fruits and vegetables to slow respiration, reduce ethylene production, and delay microbial spoilage. Ideally, produce should be cooled to its optimal storage temperature within 4–6 hours after harvest. Common methods include forced-air cooling (1–2 °C for strawberries, apples, and leafy greens), hydro-cooling (1–5 °C water for carrots, sweetcorn, peaches), vacuum cooling (suitable for leafy vegetables and mushrooms, reducing temperature from 25 °C to 2–5 °C within 30 minutes under 4–6 kPa), and package icing (for broccoli, spinach). Precooling significantly extends shelf life, for example, strawberries can last 5–7 days longer when precooled rapidly compared to ambient handling. The choice of method depends on commodity characteristics, perishability, and packaging type. Proper precooling minimizes weight loss, maintains firmness, and ensures that produce enters storage or transportation at an optimal physiological state, enhancing overall shelf stability. Commercially the forced air pre-cooling systems of 3-5 tonnes capacity costing Rs. 5-7 lakhs are available.

- ## Washing

Washing is a primary post harvest step for maintaining the quality and safety of fresh fruits and vegetables. It removes field heat, dirt, pesticide residues, and microbial contaminants from the surface. Clean potable water or sanitizing solutions are used depending on the commodity. Typical sanitizers include chlorine (50–200 ppm), peracetic acid (80–150 ppm), or electrolyzed water. Ozonated water (0.5–2ppm) and slightly acidic electrolyzed water are increasingly used as eco-friendly options. Washing is often done in dump tanks, spray washers, or flume systems at low water temperatures (5–15 °C) to reduce microbial load. Apples, mangoes, cucumbers, tomatoes, and leafy vegetables benefit significantly from effective washing. To avoid cross-contamination, wash water must be regularly sanitized and recycled carefully. This step not only enhances food safety but also prepares produce for subsequent treatments like waxing, coating, or packaging, thus indirectly contributing to shelf life extension during storage and distribution. The overhead and rotary type washing systems made of food grade stainless steel (capacity: 1 tonnes/h, cost: Rs. 4-5 lakhs) are commercially available which are suitable for washing of different types of fruits and vegetables.

- **Ozone Treatment**

Ozone (O_3) is a powerful oxidizing agent used for postharvest treatment of fresh fruits and vegetables to extend shelf life by reducing microbial contamination, ethylene levels, and surface-borne pathogens. Ozone can be applied as a gaseous treatment (0.1–0.3 ppm for continuous storage atmosphere or 2–10 ppm for short-term shock treatments) or as ozonated water wash (0.5–2 ppm). Unlike chlorine, ozone decomposes into oxygen without leaving harmful residues, making it an eco-friendly sanitizing method. It has been successfully applied in apples, berries, table grapes, tomatoes, and leafy vegetables to delay microbial spoilage and reduce decay during storage. For climacteric fruits like bananas and mangoes, ozone lowers ethylene concentration in storage chambers, thereby slowing ripening. Careful control is needed as high ozone levels may cause oxidative damage to tissues. Integration with cold storage or modified atmosphere packaging enhances effectiveness and ensures 2–3 times longer shelf stability compared to untreated produce. Aqueous type ozone washing systems of 1 tonnes/h are costing Rs. 5-6 lakhs whereas pilot scale ozone generation systems (max. flow rate of 10 L/h) are available at around Rs. 1.5 lakhs.

- **Ultraviolet(UV) Light**

Ultraviolet (UV) light, particularly UV-C (wavelength 200–280 nm), is used for non-thermal decontamination of fresh horticultural produce. UV-C irradiation at doses of 0.25–5 kJ/m^2(5-10 mins treatment) effectively inactivates surface microorganisms, fungi, and viruses by causing DNA damage, thereby delaying spoilage. It is applied through conveyorized UV chambers or portable UV lamps. Commodities like tomatoes, cucumbers, strawberries, mangoes, apples, and lettuce have shown improved shelf life and reduced postharvestdecayunderUVtreatment.Treatmentisusuallyperformedon washedanddriedproduceto ensure uniform exposure. Overexposure, however, may cause tissue damage or discoloration. UV-C, when integrated with cold storage or modified atmosphere packaging, can extend the shelf life of fruits and vegetables by 30–50%. Portable UV treatment system of 150-200 kg/h capacity costs around Rs. 50,000/-.

- ## Drying and Dehydration

Drying and dehydration are among the oldest and most widely used techniques for extending the shelf life of fresh fruits and vegetables by reducing the water activity, thereby inhibiting microbial growth and enzymatic activity. Traditionally sun drying is mostly followed by the farmers which take longer drying time and product quality is not maintained. Conventional hot-air drying operates at 50–60 °C, while advanced methods like freeze-drying (−40 to −50 °C under vacuum) and microwave-assisted drying (0.3-1 kW) allow faster moisture removal with better nutrient and colour retention. Fluidized bed dryers and solar cabinet dryer dryers (temperature increase 8-12° than ambient) are also solar tunnel dryers (temp >7-8°C than ambient) used for large-scale applications. The process reduces weight and volume, enabling easy storage and transportation. Grapes (raisins), figs, bananas, onion flakes, and tomato powder are prominent examples of dehydrated produce. Maintaining final moisture content below 10% and water activity below 0.6 is critical for microbial stability. Packaging in moisture-proof containers after drying is essential to avoid rehydration. Recent innovations include hybrid drying techniques (solar-assisted with heat pumps) for energy efficiency and improved product quality.

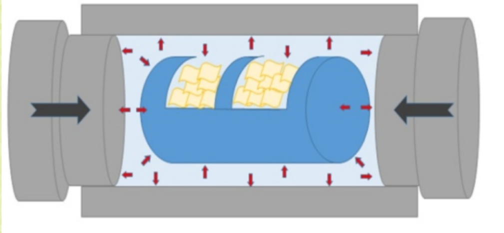
Dryer Type	Capacity (kg/batch)	Cost (Rs.lakh)	Suitable Commodities
Tray Dryer (Electric)	300-500	7-10	Fruits (apple, banana, mango), vegetables (carrot, tomato), herbs, spices
Solar Cabinet Dryer	100-200	3-5	Herbs, chilies, medicinal plants, banana/mangoslices
Solar Tunnel Dryer or Solar Greenhouse Dryer (Hybrid/Passive)	1-2 tonnes	10-12	Mango slices, banana, grapes/raisins, onions, chilies

- ## Irradiation

Food irradiation uses ionizing radiation, primarily gamma rays (from Cobalt-60), electron beams (up to 10 MeV), or X-rays, to extend shelf life and ensure microbial safety of fresh horticultural produce. The radiation dose ranges from 0.25–1.0 kGy for sprout inhibition (potato, onion), 1–3 kGy for insect disinfestation (mango, citrus), and 1–5 kGy for microbial reduction in leafy greens, strawberries etc. Irradiation disrupts DNA of microorganisms and pests, thereby delaying spoilage without significantly raising product temperature. It also delays ripening and senescence in climacteric fruits such as mangoes, papaya, and guava. The technology is particularly useful for quarantine treatments in export commodities, as it replaces chemical fumigants. Packaging must be radiation-resistant (polyethylene, PET, polypropylene). Irradiation preserves vitamins and antioxidants to a large extent, though slight losses in sensitive compounds (like vitamin C) may occur. This safe, WHO-approved technology is gaining acceptance globally for maintaining food safety and marketability. Though promising, because of high cost, this technology is more suitable at industrial scale. Farmers can form a FPO in a cluster and adopt this technology for shelf life enhancement of their produce.

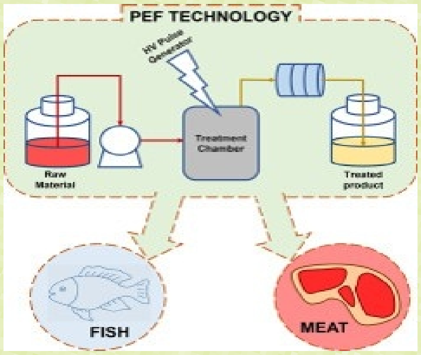
India operates 19 officially licensed gamma irradiation plants, including dedicated onion treatment units like those at Lasalgaon (KRUSHAK). The Lasalgaon facility alone has irradiated around 1,000 tonnes of onions and includes an on-site 250-tonne cold storage. The capital investment for a basic low-dose gamma irradiation unit in India is around Rs. 6 crore, inclusive of building, cobalt-60 source, and conveyors. For larger commercial or fully integrated irradiation projects (including cold storage, utilities, and packaging), costs escalate to Rs. 15–20 crore, with full-scale multi-component facilities potentially exceeding Rs. 30crore.

• High Pressure Processing (HPP)



High Pressure Processing (HPP) is a non-thermal preservation technique that extends the shelf life of fresh produce by inactivating microorganisms and enzymes while preserving nutritional and sensory qualities. The technology involves subjecting food to hydrostatic pressures of 300–600 MPa for holding times of 3–10 minutes, typically at ambient or chilled temperatures (4–25 °C). The process is uniform and independent of size or geometry, making it suitable for packaged foods without chemical preservatives. For fresh fruits and vegetables, HPP is particularly effective for juices (orange, pomegranate, guava), avocado pulp, guacamole, and fresh-cut salads. The process disrupts microbial cell membranes and enzyme activity without significantly affecting small molecules like vitamins, flavors, and pigments. Shelf life extensions of 2–4 times compared to untreated fresh produce ispossible with this technique. Packaging materials need to be flexible and water-resistant (polyethylene or PET-based) to withstand high pressure. HPP has gained commercial acceptance due to its clean-label appeal.

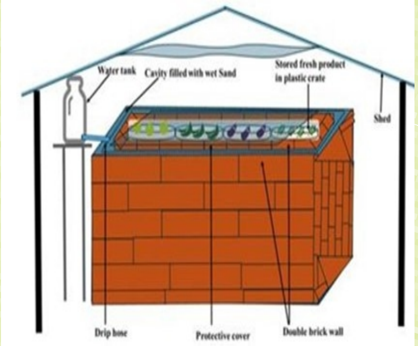
• Pulsed Electric Field (PEF)



Pulsed Electric Field (PEF) technology uses short bursts of high voltage (10–50 kV/cm) electric pulses applied for microseconds to milliseconds to inactivate microorganisms and induce cell membrane permeabilization (electroporation). It is a non-thermal method suitable for liquid and semi-liquid horticultural products such as fruit juices (apple, orange, watermelon, grape) and tomato-based beverages. PEF treatments are generally carried out at ambient or slightly elevated temperatures (<40 °C) to minimize thermal degradation. The technology effectively reduces microbial load while maintaining vitamins, color, and flavor. Additionally, PEF improves juice yield and extraction efficiency in grapes, olives, and sugar beet by enhancing cell disruption. Shelf life extensions of 1–3 weeks are possible under cold storage. However,enzymes like polyphenoloxidase may require combined treatments (e.g., PEF with mild heat).Continuous-flow PEF systems with treatment chambers are increasingly being adopted for industrial-scale juice preservation due to their energy efficiency and minimal processing impact.

Storage systems for shelf life enhancement of fresh commodities

- **Zero energy cooling chamber**



The Zero Energy Cool Chamber (ZECC) is a low-cost, non-refrigerated storage structure designed to extend the shelf life of perishable fruits and vegetables using the principle of evaporative cooling, without requiring electricity. It is built with locally available materials such as bricks, sand, bamboo, and gunny bags, consisting of a double-walled brick chamber with a sand filled cavity kept moist by regular watering and covered with wet gunny bags to enhance evaporation. This process lowers the storage temperature by about 10–15°C below ambient and maintains a high relative humidity of 90–95%, which helps reduce physiological weight loss, wilting, and microbial spoilage. ZECC is particularly suitable for storing commodities like mango, guava, papaya, tomato, cucumber, and leafy vegetables, effectively enhancing their shelf life by 2–6 days compared to ambient conditions, although it is unsuitable for low-humidity storage crops like onion, garlic, and potato. Its main advantages include low construction and operating cost and eco-friendliness. It has a storage capacity of 100–500 kg, and requires a low investment ₹ 2,000–10,000.

- **Evaporative cooling systems**

Evaporative cooling systems are low-energy, environmentally friendly technologies that utilize the natural principle of water evaporation to lower air temperature and increase humidity, making them highly suitable for the short-term storage and preservation of perishable fruits and vegetables. When hot, dry air passes over a wet surface or through a wetted medium, water evaporates by absorbing latent heat, which cools the surrounding air; this cooled, humidified air reduces produce respiration rate, water loss, wilting, and microbial spoilage. These systems include simple structures such as Zero Energy Cool Chambers (ZECCs), which use brick and sand with wet gunny covers, as well as advanced setups like pad-and-fan systems, clay pot coolers, and evaporative shelves, each varying in efficiency and cost. Typically, evaporative cooling can reduce the temperature by 10–15 °C below ambient and maintain relative humidity of 85–95%, which is ideal for fresh produce such as tomatoes, cucumbers, leafy greens, mangoes, papayas, and guavas, though it is unsuitable for low-humidity crops like onions, garlic, and potatoes. These systems are particularly effective in hot and dry climates, are inexpensive compared to mechanical refrigeration, but their efficiency decreases in high-humidity environments. This storage system is less energy intensive, lower operating cost and best suited for smallholder farmers and packhouses in hot, dry climates, with 200 kg to multi-tonne capacity options and costs ranging from ₹15,000 for small systems to ₹ 3.0 lakhs for commercial units.

- **Earth air heat exchanger-EC based storage system**

Keeping in view of the limitations of evaporative cooling based systems, various axillary systems was found to be integrated with the ECS. In this type of system earth air heat exchanger is used to cool the air 1.5m beneath the soil. The systems like earth air heat exchanger (EAHE) integrated with the evaporative cooling found to the reduction of temperature up to 22.6-25.5°C. In this type of system only EAHE reduces temperature up to 25°C-27°C and hence helped for enhancing the cooling efficiency as well as cooling capacity of the ECS. The handling capacity, cost and energy required for this system is 1 tonne, 1.75 lakhs and 250 W, respectively.

- **Ventilated storage systems**

Ventilated storage systems are mainly suitable for the fresh horticultural commodities which are sensitive to the high humidity as well as low temperature like onion, garlic etc. where required temperature in the range of 20-30°C and humidity less than 70-75%.

- **All Side Ventilated Onion Storage Structure**

This is the improved design of conventional natural ventilated system developed at ICAR-CIAE, Bhopal. The structure with 1 tonne capacity fabricated using wooden strips keeping in view of all side effective aeration to the stored lot. There is reduction in rotting losses by 58% over conventional practices in 60 days of storage period. The cost of the storage unit is Rs. 15000/-.

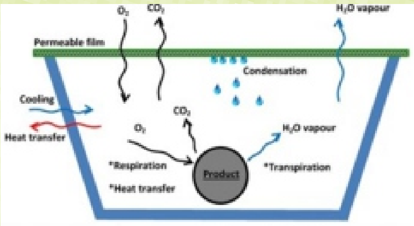
- **Modular Onion Storage Structure (Model-I, 1tonne Capacity)**

The structure is foldable modular innature. The storage unit equipped with sensor based automated aeration system. The structure has arrangement for easy filling and discharge system. The storage system is suitable to store rabi harvest of the onion during rainy season. It is made from lightweight, corrosion and UV resistive FRP material. There is reduction in total storage losses by 56 % over conventional practice. The cost of the single storage unit (without blower) is Rs. 20000/-.

- **Modular Onion Storage Structure (Model-II, 3 tonne Capacity)**

The modular storage system designed and scaled-up for storage of onion up to 3 tonne. The multiple units may be arranged in array for matching the required capacity with single air station unit. There is reduction in total storage losses by 56% over conventional practice. The cost of the single storage unit (without blower) is Rs. 35000/-. A 1000 CFM capacity blower can aerate about 04 storage units.

- **Modified atmosphere storage system**



(Bilay et al, 2016)

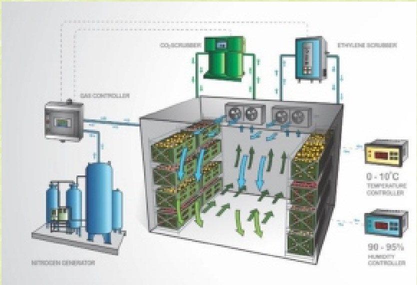
Modified atmosphere storage systems for fruits and vegetables are advanced post-harvest technologies that extend shelf life and preserve quality by altering the composition of gases surrounding the stored produce. In these systems, the concentrations of oxygen, carbon dioxide, and nitrogen are carefully controlled to slow down respiration, delay ripening, and suppress microbial activity. Typically, oxygen levels are reduced (2–5%) and carbon dioxide levels are elevated (3–10%) depending on the commodity, while nitrogen is used as a filler gas to maintain balance. Modified atmosphere can be achieved either passively, through the natural respiration of the produce in sealed environments, or actively, by introducing a pre-determined gas mixture. This technique is widely used for apples, pears, bananas, grapes, and leafy vegetables, as it helps maintain freshness, firmness, color, and nutritional quality while reducing post-harvest losses. Temperature and relative humidity control are often integrated with the system to maximize its effectiveness. Compared to conventional cold storage, modified atmosphere storage offers significant advantages by extending storage periods from weeks to several months, enabling long-distance transportation and market flexibility. However, the system requires precise monitoring, airtight storage chambers, and careful commodity-specific adjustments to avoid physiological disorders or off-flavors, making it a high-value but technically intensive method for post-harvest management.

- **CIAE MA storage system:**

CIAE Bhopal has been developed a pilot scale MA storage system suitable for different horticultural produce with selection of appropriate plastic film lining of the structure wall, which acts as barrier for the exchange of the gases. The R&D efforts are also going on for its scale-up up to cargo/truck size for its application in transport system. This tailor made system can easily be adopted for the storage and distant transportation of sub-tropical fruits like mango, guava, tomato etc. Total capacity 100 kg/batch and cost Rs. 25000/-. The tomato stored in this system fetches 21 days of shelf life at ambient temperature and 35 days at 10°C.

Commodity Type	Examples	Suitability for MA Storage	Recommended O2 (%)	Recommended CO2 (%)	Storage Temperature (°C)	Expected Shelf Life
Fruits (Climacteric)	Apples, Pears, Bananas, Mangoes, Kiwifruit	Highly suitable slows ripening and senescence	2–5	3–10	0–5 (apples/pear), 12–15 (bananas)	2-6 months
Fruits (Non-climacteric)	Grapes, Berries, Cherries, Citrus	Suitable; reduces decay and maintains quality	3–8	5–10	0–5 (berries), 0–10 (grapes)	2 – 3 months
Leafy Vegetables	Lettuce, Spinach, Cabbage, Kale	Highly suitable; slows senescence and chlorophyll degradation	2–5	5–10	0–2	2 – 4 weeks
Root Vegetables	Carrots, Radish, Beets	Suitable; slows metabolic activity and microbial decay	3–5	3–8	0–2	1 – 3 months
Bulbs	Onions, Garlic	Moderately suitable; reduces sprouting and disease	1–3	2–5	0–2	1 – 6 months
Cucurbits	Cucumber, Zucchini, Pumpkin	Suitable; slows respiration and softening	2–5	3–8	7–10	8-10 weeks

- **Control atmosphere storage system**



Control Atmosphere (CA) storage systems for fresh horticultural produce are advanced post-harvest technologies designed to significantly extend the storage life of fruits and vegetables by precisely regulating the composition of gases, temperature, and relative humidity within a sealed environment. Unlike Modified Atmosphere Storage (MAS), where the atmospheric conditions adjust passively due to the produce's respiration, CA storage actively monitors and maintains low oxygen levels (typically 1–3%) and elevated carbon dioxide levels (2–10%) according to commodity-specific requirements. This precise control slows respiration, delays ripening, inhibits microbial growth, and minimizes physiological disorders such as senescence, browning, and textural degradation. CA storage is particularly suitable for high- value, long-storage crops like apples, pears, kiwifruit, grapes, and certain stone fruits, as well as select vegetables like leafy greens and root crops that are sensitive to metabolic stress. The system integrates airtight storage chambers, automated gas monitoring and injection systems, and refrigeration to maintain optimal low temperatures (0–12 °C) and relative humidity (85–95%), ensuring uniform quality throughout storage. While CA storage requires higher initial investment and technical expertise compared to conventional or modified atmosphere storage, it allows long-term preservation—often extending storage life from several weeks to several months—facilitates off-season marketing, and reduces post-harvest losses, making it an essential technology for commercial horticultural operations.

Commodity Type	Examples	O_2 (%)	CO_2 (%)	Temperature (°C)	Relative Humidity (%)	Storage Duration / Notes
Climacteric Fruits	Apples	1–2	1–3	0–1	90–95	6–12 months depending on variety; slows ripening and maintains firmness
	Pears	1–2	1–3	0–0.5	90–95	Up to 6 months; prevents over-ripening and decay
	Kiwifruit	1–2	2–5	0	90–95	4–6 months; maintains firmness and delays senescence
	Bananas	2–5	3–5	13–14	90–95	Extends shelf life; careful to avoid chilling injury

	Mangoes	2–3	4–6	12–13	85–90	Delays ripening; extends shelf life by several weeks
Non-Climacteric Fruits	Grapes	1–3	5–10	0–1	90–95	2–3 months; prevents microbial decay
	Berries (Strawberries, Blueberries)	2–5	5–10	0–1	90–95	2–3 weeks; reduces decay and preserves color
	Citrus (Oranges, Lemons)	2–3	2–5	4–6	85–90	1–2 months; maintains firmness and reduces decay
Leafy Vegetables	Lettuce, Spinach, Cabbage	1–2	5–10	0–1	95–98	2–4 weeks; slows wilting and chlorophyll degradation
Root Vegetables	Carrots, Beets, Radish	2–3	3–5	0–1	90–95	4–6 months; preserves firmness and reduces microbial spoilage
Bulbs	Onions, Garlic	1–2	2–5	0–2	65–70	Several months; reduces sprouting and disease
Cucurbits	Cucumber, Zucchini, Pumpkin	2–3	3–5	7–10	90–95	2–4 weeks; slows respiration and softening

- **Cold Storage**

Cold storage of fresh horticultural produce is a widely adopted post-harvest technology aimed at extending shelf life, preserving quality, and reducing losses during storage and transportation. By maintaining low temperatures—typically ranging from 0 °C to 15 °C depending on the commodity—cold storage slows down respiration, enzymatic activity, and microbial growth, thereby delaying ripening, senescence, and spoilage. Relative humidity is also carefully controlled, usually between 85% and 95%, to prevent dehydration, shriveling, or surface mold development. Cold storage is suitable for a broad range of fruits and vegetables, including apples, pears, grapes, mangoes, bananas, carrots, onions, and leafy greens, with temperature and humidity requirements tailored to each commodity. Pre- cooling of produce before storage is often recommended to remove field heat and enhance cooling efficiency.

While the initial investment in cold storage infrastructure can be significant, the technology plays a critical role in maintaining sensory attributes, nutritional quality, and market value of fresh horticultural commodities, enabling year-round availability, facilitating long-distance transport, and reducing post-harvest losses for both commercial and small-scale producers. The cold storage system also promoted through the various govt. scheme. Still, the technology is much cost and energy intensive, for storage of 1 tonne it involves about 7-8 lakhs of investment and 3.0 kw-h/tonne of energy requirement.

Commodity Type	Examples	Storage Temperature (°C)	Relative Humidity (%)	Expected Shelf Life
Fruits (Climacteric)	Apples	0–1	90–95	4 – 8 months
	Pears	0–0.5	90–95	2 – 5 months
	Bananas	13–14	90–95	2 – 4 weeks
	Mangoes	12–13	85–90	2 – 3 weeks
Fruits (Non-Climacteric)	Grapes	0–1	90–95	2 – 3 months
	Berries (Strawberries, Blueberries)	0–1	90–95	5 – 7 days
	Citrus (Oranges, Lemons)	4–6	85–90	1 – 3 months
Leafy Vegetables	Lettuce, Spinach, Cabbage	0–1	95–98	1 – 4 weeks
Root Vegetables	Carrots, Beets, Radish	0–1	90–95	1 – 3 months
Bulbs	Onions, Garlic	0–2	65–70	1 – 8 months
Cucurbits	Cucumber, Zucchini, Pumpkin	7–10	90–95	10 – 14 Days

- **Refrigerated storage system**

Refrigerated storage of fresh horticultural produce is a post- harvest technology that combines low temperature with controlled humidity to preserve the quality, freshness, and nutritional value of fruits and vegetables during storage and transportation. Unlike conventional cold storage, refrigerated storage often involves mechanically cooled rooms, refrigerated trucks, or containers and retail as well household refrigerated cabinets that provide precise temperature control, typically ranging from 0 °C to 7 °C depending on the commodity, along with relative humidity levels of 85–95% to prevent dehydration and wilting. The estimated cost for 1-tonne capacity refrigerated storage system would be between Rs. 3.5 lakhs and Rs. 7 lakhs, depending on the desired specifications and features of the commodities.

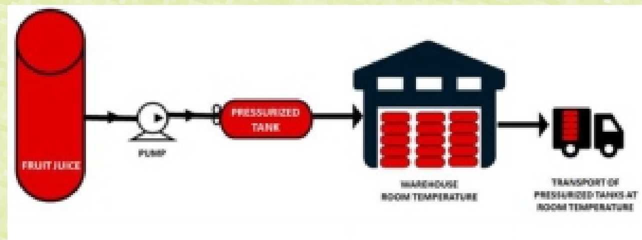
- **Pusa Sun fridge**

The Pusa Farm Sun Fridge (Pusa-FSF) is an innovative, off-grid, solar-powered cold storage solution to help smallholder farmers preserve their produce affordably and sustainably. This battery-less refrigeration system combines solar energy with evaporative cooling techniques. During the day, roof top solar panels (around 5 kW capacity) power a 1.5-ton AC unit to maintain internal temperatures between 3–4 °C, while circulating water via a submersible pump through overhead PVC pipes. At night, cooled water acts as thermal "water battery", enabling passive evaporative cooling that keeps temperatures within 8–12 °C, even without electricity. The system is recommended for storage of perishable commodities such as tomatoes, cucumbers, leafy greens, okra, brinjal, guava, papaya, mango, and berries etc. The unit can store approximately 2 tonnes of perishable produce costing around 5-5.5 Lakhs.

- **Solar operated cold storages**

Solar-operated cold storages are innovative, eco-friendly solutions designed to address the post-harvest challenges of perishable horticultural commodities, particularly in regions with limited or unreliable electricity supply. These systems utilize photovoltaic (PV) solar panels to generate electricity, which powers refrigeration units for maintaining low and stable temperatures, typically between 2–15 °C depending on the commodity, along with relative humidity control to prevent dehydration or fungal growth. Some advanced models are integrated with battery banks or thermal energy storage systems (such as phase change materials or chilled water reservoirs) to ensure round-the-clock cooling even during non-sunlight hours. Solar cold storages are especially suitable for storing fruits, vegetables, dairy, fish, and other perishables at the farm-gate level, reducing post-harvest losses, extending shelf life, and enabling farmers to sell produce at better market prices instead of resorting to distress sales. The estimated cost for 1-tonne capacity solar operated storage system is about 5-6 lakhs.

- **Hyperbaric Storage system**



Hyperbaric storage system for fresh fruits and vegetables is an advanced post-harvest preservation technique that involves storing produce under high- pressure conditions, typically ranging from 50 to 100 MPa, at either room or refrigerated temperatures. Unlike conventional cold storage or controlled atmosphere systems, hyperbaric storage slows down physiological and biochemical processes, such as respiration, ethylene production, ripening, and microbial activity, without the need for chemical preservatives or extreme refrigeration. By maintaining produce under constant high pressure, cellular metabolism is suppressed, leading to extended shelf life, improved firmness, retention of color, flavor, and nutrients, and reduced microbial spoilage. This system is particularly promising for highly perishable commodities such as berries, leafy vegetables, tomatoes, peaches, and mangoes, which are prone to rapid deterioration under ambient conditions. Hyperbaric storage also offers the advantage of reducing energy consumption compared to continuous low-temperature storage, making it a potential sustainable solution for long-term preservation. The estimated cost for 1-tonne capacity hyperbaric storage system is about 20-56 lakhs.

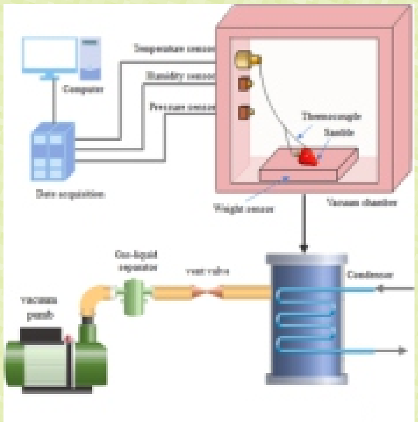
Recommended Hyperbaric Storage Conditions for Fresh Produce:

Commodity	Pressure Range (MPa)	Temperature (°C)	RH (%)	Observed Effect / Shelf-life Extension
Strawberries	50–75 MPa	5–10	90–95	Reduced microbial growth, delayed softening, color retention (up to 20 days vs. 5–7 days in cold storage).
Tomatoes	50 MPa	20–25 (room temp)	85–90	Slowed ripening, delayed color change, maintained firmness for ~30 days.
Mangoes	50–80 MPa	10–15	85–90	Reduced respiration, delayed ripening, extended shelf life by 1.5–2x.
Peaches	75–100 MPa	5–10	90–95	Maintained firmness, reduced browning, extended storage to ~30 days.

Commodity	Pressure Range (MPa)	Temperature (°C)	RH (%)	Observed Effect / Shelf-life Extension
Leafy Vegetables (Spinach, Lettuce)	40–60 MPa	5–10	90–95	Delayed yellowing, reduced respiration, shelf life extended by ~2 weeks.
Carrots	60–80 MPa	5–10	95–98	Maintained color, crispness, reduced microbial spoilage.
Apples	50–75 MPa	0–5	90–95	Reduced ethylene production, delayed softening, extended storage up to several weeks.
Grapes	50–70 MPa	5–10	90–95	Retained firmness, reduced fungal growth (Botrytis), extended life up to 30–40 days.

- **Hypobaric storage system**

Hypobaric storage system for fresh fruits and vegetables is an advanced post-harvest technology that preserves perishable produce by maintaining storage conditions under low or sub- atmospheric pressures, typically ranging from 50 to 200 mm Hg (well below normal atmospheric pressure of 760 mm Hg). By lowering the surrounding pressure, this system significantly reduces the partial pressure of oxygen, thereby slowing respiration, ethylene production, ripening, and microbial activity, while simultaneously facilitating the continuous removal of metabolic gases and moisture released from the produce. The reduced oxygen levels and enhanced ventilation help in delaying senescence, maintaining firmness, color, and nutritional quality, and extending the storage life of highly perishable commodities such as strawberries, mangoes, bananas, guavas, leafy greens, and cut flowers. Unlike conventional cold storage, hypobaric systems often operate at moderate refrigeration temperatures (5–15 °C), which minimizes chilling injury in sensitive crops.



Packaging systems for shelf life enhancement

- **MA packaging**

Modified Atmosphere Packaging (MAP) is a sophisticated post-harvest technology used to extend the shelf life and maintain the quality of fresh fruits and vegetables by altering the composition of gases surrounding the produce within a sealed package. This system works by reducing oxygen levels and increasing carbon dioxide and sometimes nitrogen levels inside the packaging, which slows down respiration, ethylene production, and

microbial growth while delaying ripening and senescence. MAP can be implemented using specialized films that have controlled gas permeability, or through active modification where gases are flushed into the package to achieve the desired atmosphere. This packaging technique is particularly effective for high-respiring and perishable commodities such as berries, grapes, tomatoes, leafy vegetables, mushrooms, and tropical fruits like mangoes and papayas. The technology allows precise control over oxygen (typically 1–5%), carbon dioxide (5–15%), and nitrogen (balance) concentrations, customized according to the specific respiration and sensitivity of the commodity. By maintaining optimal humidity and gas composition, MAP prevents moisture loss, preserves texture, color, and flavor, and reduces the incidence of microbial spoilage. Compared to conventional packaging, MAP offers substantial benefits in extending shelf life by 2–4 times. The total packaging cost per kilogram, ranging from Rs. 2.75 to Rs. 5.00.

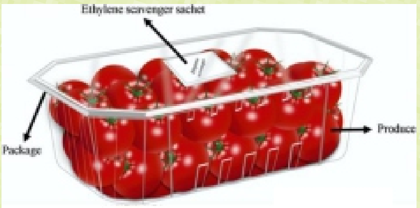
- **Micro-perforated packaging**

Micro-perforated packaging is an advanced post-harvest packaging technology designed to extend the shelf life and maintain the quality of fresh fruits and vegetables by regulating the exchange of gases and moisture between the packaged produce and the surrounding environment. This system uses films with microscopic holes, usually ranging from 50 to 200 microns in diameter, that are strategically engineered in terms of number, size, and distribution to balance the respiration rate of the produce with the surrounding atmosphere. The micro-perforations allow controlled levels of oxygen and carbon dioxide to diffuse in and out of the package, creating a modified atmosphere that slows respiration, delays ripening, and reduces ethylene accumulation while preventing anaerobic conditions that could lead to off-flavors or microbial spoilage. In addition, the perforations help manage humidity, reducing condensation inside the package and thereby minimizing the risk of fungal growth while maintaining freshness. Micro-perforated packaging is particularly suitable for high-respiring and moisture-sensitive commodities such as berries, grapes, cucumbers, leafy vegetables, tomatoes, and mushrooms, which deteriorate rapidly under normal packaging. This is a cost-effective packaging technology, and does not require complex storage infrastructure. The packaging cost for this type of system is comes around Rs.2-3 per kg.

- **CIAE-Micro-perforation based MA Packaging**

For retail-size Modified Atmosphere (MA) packaging, the optimal perforation area for tomatoes is 0.0019%, for 60 µm LDPE and LLDPE films to achieve the desired gas composition for prolonged storage. Tomatoes can be packed in these optimized perforated MA packages up to 28 days at 25 °C and 45 days at 10 °C. This approach helps slow respiration, reduce spoilage, and extend shelf life while preserving freshness, firmness, and sensory quality of tomatoes during storage and distribution.

- **Active packaging**



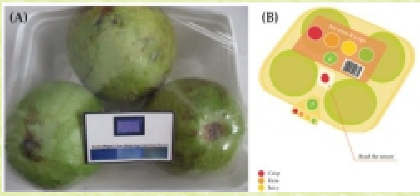
Active Packaging of Fruits and Vegetables is an advanced packaging technology designed not only to contain and protect produce but also to actively interact with it and its surrounding environment to extend shelf life, maintain quality, and ensure safety.

Unlike traditional packaging, which serves as a passive barrier, active packaging incorporates functional components such as oxygen scavengers, carbon dioxide emitters/absorbers, ethylene scavengers, moisture regulators, and antimicrobial or antioxidant-releasing agents. These components help in controlling respiration rate, delaying ripening, reducing microbial growth, and preventing moisture loss, thereby slowing down deterioration. For example, ethylene scavenging sachets or films can remove ethylene gas emitted by climacteric fruits, delaying over-ripening, while antimicrobial coatings inhibit the growth of spoilage organisms. Moisture-regulating films prevent condensation inside packages, reducing fungal growth. The application of active packaging in fruits and vegetables is particularly important due to their high perishability and sensitivity to environmental conditions. This technology enhances postharvest handling, supports long-distance transportation, reduces food waste, and meets consumer demand for fresh, safe, and high-quality produce. Total packaging cost for active packaging ranges between ₹3.0–5.5 per kg of fruits and vegetables, depending on the system used.

- **Intelligent packaging**

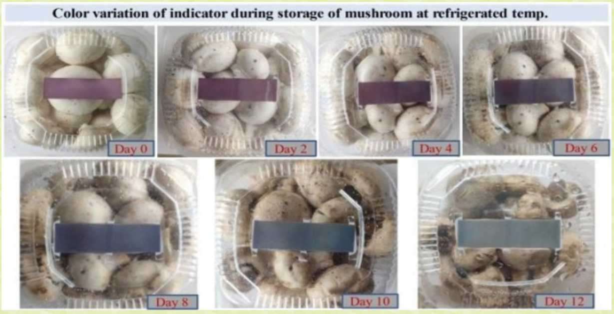
Intelligent packaging of fresh fruits and vegetables refers to packaging systems that actively monitor the condition of the packaged produce and provide real-time information about its freshness, safety, and quality throughout the supply chain. Unlike traditional packaging, which serves only as a passive barrier, intelligent packaging incorporates advanced components such as sensors, indicators, and data carriers to detect changes in the internal or external environment. Common technologies include time– temperature indicators (TTIs) that reveal exposure to temperature abuse, gas sensors that detect ripening-related gases like ethylene or spoilage-related gases like CO , and freshness indicators that change color based on pH or microbial activity. Radio Frequency Identification (RFID) tags and QR codes are also used to track produce from farm to shelf, offering full traceability and supply chain transparency. These systems are especially valuable for highly perishable items such as berries, leafy greens, tomatoes, and tropical fruits, where quality degradation can occur rapidly. Intelligent packaging not only helps retailers and consumers assess product freshness at a glance but also reduces food waste by improving inventory management and allowing more precise handling decisions. As consumer demand for quality and safety increases, and as global supply chains grow more complex, intelligent packaging is becoming a vital tool in modern agriculture and food distribution, enhancing both efficiency and sustainability.

- **Smart packaging**



Smart packaging of fresh fruits and vegetables refers to advanced packaging systems designed to monitor, preserve, and enhance the quality and safety of produce throughout the supply chain. This innovative approach integrates technologies such as sensors, indicators, and data carriers (e.g., RFID tags and QR codes) to provide real-time information about the condition of the packaged produce. Smart packaging can include time-temperature indicators that reveal exposure to unsuitable temperatures, gas sensors that detect spoilage-related compounds like ethylene, and humidity regulators that prevent moisture build-up. By offering continuous monitoring, smart packaging not only helps reduce food waste but also enables better inventory management and traceability, improving consumer confidence and food safety.

- **CIAE Freshness Indicator based smart packaging of mushroom and sapota**



A standard size filter paper of selected grade was cut (1.5 cm × 5 cm) and used as carrier for coating indicator solution on to it. Paper strip was placed in a centrifuge tube and selected indicator solution dye was then added to fully dip the filter paper. It was then centrifuged for 15 minutes in a centrifuge machine to coat the dye over filter paper. The filter paper along with the coated dye was dried overnight in oven at 40˚C. Color change profile of developed freshness indicator during storage of fresh mushroom at 5°C shown that at day 0 - pH was 6.25 of mushroom and Indicator color was lavender when it was fully fresh, at day 8 - the pH was 7.83 of mushroom and Indicator color was violet when it was still fresh and at the end of the 12 days - pH exceeded 8.45 of mushroom and Indicator color was dusty blue when it had spoiled. Color change profile of developed freshness indicator during storage of sapota at ambient temperature shown that, at day 1 - pH was 5.86 of sapota and Indicator color was Light yellow when it was fully fresh, at day 8 - pH was 6.24 of sapota and Indicator color was also Light yellow when it was still fresh and at day 16 - pH decreased towards the end of the storage period, it 5.32 of sapota and Indicator color was Light pink, when it had spoiled. The color of freshness indicator changes and communicates the freshness level of stored mushroom and sapota.

Preservation Techniques for Fruits and Vegetables to Enhance Shelf Life

- **Chemical Methods**
- **Edible Coatings & Films for Fruits and Vegetables**

Edible coatings and films are thin, consumable layers applied to fruits and vegetables to extend shelf life by reducing moisture loss, controlling respiration, and acting as barriers to oxygen and microbial contamination. They are typically formulated from natural materials such as polysaccharides (pectin, starch, alginate, cellulose derivatives, chitosan), proteins (soy protein, whey protein, casein, gelatin), lipids (beeswax, carnauba wax, fatty acids), or composite blends to improve mechanical strength and barrier properties. These coatings may also incorporate antioxidants, antimicrobials, or nutraceuticals to further enhance preservation.

Coatings are applied through dipping, spraying, or brushing, ensuring a uniform and thin layer that does not affect the sensory quality of the produce. For best results, coated fruits and vegetables should be stored under controlled temperature and humidity conditions—generally 0–10°C with 85–95% relative humidity depending on the commodity. Combining edible coatings with cold storage, modified atmosphere packaging, or other postharvest treatments can significantly delay ripening, reduce microbial spoilage, and preserve firmness, color, and nutritional quality.

Edible coating materials, storage conditions, and their effects on shelf life:

Produce	Coating Material	Storage Conditions	Shelf-Life Extension / Benefits
Apples	Chitosan (1–2%)+ Ascorbic Acid	4–8°C, 90–95% RH	Reduces browning, weight loss; extends shelf life by 10–14 days
Mangoes	Aloe Vera Gel (1.5%) + Glycerol	10–13°C, 85–90% RH	Delays ripening, maintains irmness; shelf life increased by 8–10 days
Strawberries	Pectin (1%) + Essential Oils (Clove/Cinnamon)	0–5°C, 90–95% RH	Controls fungal decay; xtends shelf life by 5–7 days
Tomatoes	Starch-Based Edible Film (2–3%) + Beeswax	10–12°C, 85–90% RH	Slows respiration, reduces icrobial growth; increases shelf life by 6–8 days
Cucumbers	Chitosan (1%) + Nano-Silver Particles	10–12°C, 85–90% RH	Maintains firmness and color; shelf life extended by 10–12 days
Carrots (Fresh-Cut)	Alginate (1.5%) + Calcium Chloride	0–4°C, 95% RH	Prevents dehydration and microbial spoilage; adds 7– 10 days shelf life
Citrus Fruits	Wax + Carnauba-Based Coating	5–8°C, 85–90% RH	Reduces moisture loss, retains gloss; prolongs shelf life by 14–21 days

- **Natural Preservatives:**

Natural preservatives play a crucial role in extending the shelf life of fruits and vegetables by inhibiting microbial growth and oxidative deterioration. Organic acids such as citric acid and ascorbic acid are widely used due to their ability to lower pH, create unfavourable conditions for spoilage microorganisms, and act as antioxidants to prevent enzymatic browning. Essential oils derived from clove, cinnamon, thyme, oregano, and other aromatic plants exhibit strong antimicrobial and antifungal properties, making them effective in reducing postharvest decay. Similarly, plant extracts rich in bioactive compounds such as polyphenols, flavonoids, and terpenoids—help preserve color, texture, and nutritional quality while minimizingthe need for synthetic preservatives. These natural alternatives are generally recognized as safe (GRAS) and meet consumer preferences for clean-label, chemical- free preservation methods. When combined with edible coatings or modifiedstorage conditions, natural preservatives can significantly enhance the shelf life and safety of fresh produce.

List of Natural Preservatives and Expected Shelf-Life Enhancement

Produce	Natural Preservative	Storage Conditions	Unpreserved Shelf Life	Enhanced Shelf Life
Apples	Citric Acid (1–2%) Dip	4–8 °C, 90–95% RH	5–7 days	15–18 days
Strawberries	Clove Oil (0.1–0.2%) Spray	0–5 °C, 90–95% RH	3–4 days	8–10 days
Mangoes	Ascorbic Acid (1%) + Aloe Vera Extract	10–13 °C, 85–90% RH	6–8 days	14–16 days
Tomatoes	Thyme Essential Oil (0.1%)	10–12 °C, 85–90% RH	4–5 days	10–12 days
Cucumbers	Oregano Oil (0.1–0.2%)	10–12 °C, 85–90% RH	5–6 days	12–14 days
Carrots (Fresh-Cut)	Green Tea Extract (0.5–1%)	0–4 °C, 95% RH	4–5 days	10–12 days
Citrus Fruits	Lemon Peel Extract (1%)	5–8 °C, 85–90% RH	10–12 days	25–30 days

- **Chemical Dips:**

Chemical dip solutions are commonly used to reduce microbial load, delay spoilage, and maintain the quality of fresh fruits and vegetables during postharvest storage. These solutions may include food-grade chemicals such as calcium chloride, sodium hypochlorite, hydrogen peroxide, or organic acid solutions (citric acid, ascorbic acid, acetic acid) that actas sanitizers, firming agents, or antioxidants. Calcium-based dips help strengthen cell walls, reduce softening, and maintain firmness, while chlorine- or peroxide-based dips effectively reduce microbial contamination. In case of Litchi the common chemical methods includeSO_2 fumigation, ascorbic acid dips, calcium salts, and chitosan coatings to inhibit enzymatic browning, strengthen cell walls, and reduce microbial growth. Under 0–4°C and 90–95% RH, shelf life can be extended up to 10–15 days. Organic acid dips help lower pH and prevent enzymatic browning, there by preserving color and freshness. Application typically involves immersing produce for a short period, followed by draining and drying before storage. When combined with controlled temperature (0–15 °C) and high relative humidity (85–95% RH), chemical dip treatments can extend shelf life by 1.5–3 times depending on the commodity and treatment type.

Common chemical dip solutions, their concentrations, storage conditions, and expected shelf-life enhancement for fruits and vegetables:

Chemical Dip Solution	Typical Concentration	Storage Conditions	Expected Shelf-Life Enhancement
Calcium Chloride ($CaCl_2$)	1–2%	0–10 °C, 85–95% RH	1.5–2 time longer compared to untreated produce
Sodium Hypochlorite (NaOCl)	50–200 ppm	0–10 °C, 85–95% RH	1.5–2 time shelf-life increase
Hydrogen Peroxide (H_2O_2)	1–3%	0–10 °C, 85–95% RH	1.5–2.5 time longer shelf life
Citric Acid	0.5–2%	0–10 °C, 85–95% RH	1.5–2 time shelf-life extension
Ascorbic Acid	0.5–1%	0–10 °C, 85–95% RH	1.5–2 time shelf-life increase
Acetic Acid (Vinegar)	0.5–1%	0–10 °C, 85–95% RH	1.5–2 time longer preservation

- **Biological Methods**
- **Probiotic & Antimicrobial Cultures:**

The application of probiotic and antimicrobial cultures involves the use of beneficial microorganisms, such as lactic acid bacteria (LAB), Bacillus spp., or yeasts, to out compete spoilage organisms and pathogenic microbes on the surface of fresh fruits and vegetables. These beneficial cultures create a protective biofilm, produce organic acids, bacteriocins, and other antimicrobial compounds, thereby reducing microbial growth and enzymatic spoilage. When combined with proper storage conditions (0–10 °C and 85–95% relative humidity), this approach can extend the shelf life of fresh produce by 1.5–3 times compared to untreated products, while also maintaining nutritional quality and freshness.

Probiotic & Antimicrobial Cultures for Preservation

Type	Key Microorganisms	Storage Conditions	Role in Preservation	Expected Shelf-Life Enhancement
Probiotic Cultures	Lactobacillus plantarum, L. casei, Bacillus coagulans, probiotic yeasts	0–8 °C, 85–90% RH	Forms biofilm, competes with spoilage microbes	1.5–2 time (e.g., berries 3 – 6 days)
Antimicrobial Cultures	Lactococcus lactis, Pediococcus acidilactici, antifungal yeasts	0–10 °C, 90–95% RH	Produces acids, bacteriocins, inhibits pathogens	2–3 time (e.g., carrots 5 – 12 days)

- **Biochemical Treatment methods**

Biochemical treatments utilize enzymes or metabolic regulators to slow down ripening, senescence, and degradation in fruits and vegetables. These methods regulate ethylene production, respiration rates, and enzymatic activity responsible for softening and browning. For instance, 1-methylcyclopropene (1-MCP) effectively inhibits ethylene action, maintaining firmness and extending the shelf life of fruits such as apples, bananas, and mangoes. Enzyme-based treatments, like pectin methylesterase (PME), reinforce cell walls to preserve texture in strawberries and tomatoes, while polyphenol oxidase inhibitors minimize browning in cut apples and pears. Additionally, metabolic regulators including salicylic acid, jasmonic acid, and nitric oxide delay senescence and enhance resistance to microbial spoilage. Under optimal storage conditions (0–10 °C and 85–95% RH), these treatments can prolong fruit shelf life by 50–150% and vegetables by 30–100%, depending on the commodity and treatment applied.

Biochemical Treatments for Fruits and Vegetables Preservation

Treatment Type	Examples	Mechanism	Target Produce	Storage Conditions
Ethylene Inhibitors	1-Methylcyclopropene (1-MCP)	Blocks ethylene action, slows ripening	Apples, bananas, mangoes	0–10 °C, 85–95% RH
Enzyme-Based Treatments	Pectin methylesterase (PME), Polyphenol oxidase inhibitors	Reinforce cell walls, minimize browning	Strawberries, tomatoes, cut apples, pears	0–10 °C, 85–95% RH
Metabolic Regulators	Salicylic acid, Jasmonic acid, Nitric oxide	Delay senescence, enhance resistance to microbial spoilage	Various fruits & vegetables	0–10 °C, 85–95% RH

- **Preservatives Used for Fruits and Vegetables**

Preservatives are widely employed to extend the shelf life of fruits and vegetables by inhibiting microbial growth, slowing enzymatic reactions, and reducing spoilage. Commonly used chemical preservatives include organic acids such as citric acid, ascorbic acid, andacetic acid, which help prevent browning and maintain firmness. Calcium salts (e.g., calcium chloride, calcium lactate) strengthen cell walls, reducing softening and textural degradation. Natural antimicrobial compounds, such as essential oils (clove, cinnamon, oregano) and plant phenolics, provide clean-label preservation by controlling bacteria, yeasts, and molds. Additionally, edible coatings incorporating polysaccharides, proteins, or lipids serve as protective barriers, reducing moisture loss and respiration. These preservatives, when combined with proper storage conditions, help maintain quality, safety, and nutritionalvalue of produce while significantly enhancing shelf life.

Preservative	Category	Mode of Action	Typical Use
Sulfur Dioxide (SO_2)	Chemical	Antimicrobial, antioxidant, enzyme inhibitor	Dried fruits, juices
Sodium Metabisulfite	Chemical	Releases SO_2 to inhibit microbes & oxidation	Dried fruits, syrups
Potassium Metabisulfite	Chemical	Similar to sodium metabisulfite	Pickles, beverages
Sodium Benzoate	Chemical	Inhibits yeast, mold, some bacteria	Juices, purees
Potassium Sorbate	Chemical	Inhibits yeast and mold	Jams, sauces
Sorbic Acid	Chemical	Inhibits mold, yeast	Fruit-based products
Citric Acid	Acidulant/ Antioxidant	Controls pH, delays browning, chelates metals	Fresh-cut fruits
Ascorbic Acid	Antioxidant	Prevents oxidation, enzymatic browning	Fresh & processed fruits
Acetic Acid	Acidulant	Lowers pH, antimicrobial	Pickled vegetables
Malic Acid	Acidulant	pH control, antioxidant	Fruit juices, beverages
Tartaric Acid	Acidulant	pH control, antioxidant	Preserves color, flavor
Calcium Propionate	Chemical	Inhibits mold growth	Processed vegetables
Chitosan	Natural coating	Antimicrobial film, respiration barrier	Fresh-cut produce
Nisin	Biological	Bacteriocin effective against Gram-positive bacteria	Minimally processed vegetables
Pediocin	Biological	Similar to Nisin	Fresh produce
Essential Oils (e.g., Clove, Oregano, Thyme)	Natural Extract	Antimicrobial, antioxidant	Coatings, wash solutions
Plant Extracts (Neem, Aloe, Tulsi)	Natural Extract	Antimicrobial, antioxidant	Surface treatment
Hydrogen Peroxide	Sanitizer	Oxidizing agent, kills microbes	Washing fresh produce
Ozone	Sanitizer	Strong oxidant, destroys microbes	Cold storage, Washing
Peracetic Acid	Sanitizer	Oxidizing antimicrobial	Washing fruits, vegetables
Chlorine Dioxide	Sanitizer	Broad-spectrum antimicrobial	Washing, storage

Agro Produce Processing Division
ICAR-Central Institute of Agricultural Engineering
Nabi Bagh, Berasia Road, Bhopal – 462 038
Email: sukhdev0108@gmail.com I Contact No.: 07477269857