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From Cold Rooms to Smart Storage: The Science Behind Keeping Fruits and Vegetables Fresh

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Have you ever wondered why apples remain fresh in cold storage for several months, while the same fruits may become soft, shrivelled or spoiled within a few days when kept at room temperature? Or why vegetables packed in special plastic bags remain fresh longer than those left in open baskets? The answer lies in the science of postharvest storage. Fruits and vegetables are living commodities, can continue to breathe, consume stored food reserves, lose moisture and undergo several biochemical changes even after they are harvested. During this period, fruits ripen, vegetables lose their crispness, nutritional and sensory qualities, and gradually deteriorate. Microbial infections, unsuitable temperatures, excessive moisture loss and physical damage further accelerate spoilage. This makes postharvest storage one of the most important steps in the journey from farm to consumer. However, modern storage is no longer simply about keeping fruits and vegetables in a cold room. It has evolved into a sophisticated system that manages temperature, humidity, oxygen and carbon dioxide to slow down the natural ageing process. Technological advancements have taken us from conventional cold storage to modified atmosphere packaging (MAP), controlled atmosphere (CA) storage and, more recently, dynamic controlled atmosphere (DCA) storage. Each technology offers a different way of managing the environment surrounding fresh produce, with the common objective of maintaining freshness, reducing food losses and extending market availability.

Cold storage: The foundation of modern postharvest preservation

Among all postharvest technologies, cold storage remains one of the oldest, most widely adopted and essential methods of preserving fresh fruits and vegetables. As discussed in the previous section, fruits and vegetables continue to respire, just as they do when attached to the plant. They consume oxygen and release carbon dioxide, water and heat. At the same time, enzymes continue to break down cellular components, fruits soften, and microorganisms may multiply. Lowering the storage temperature slows many of these activities, thereby delaying ripening, ageing and spoilage. Modern cold storage facilities are designed to maintain three important conditions:

Temperature: Each commodity requires an appropriate storage temperature. Apples, grapes and leafy vegetables generally benefit from refrigeration, whereas tropical fruits such as banana and mango can suffer chilling injury if exposed to excessively low temperatures.

Relative humidity: Maintaining suitable moisture levels prevents excessive water loss, shrivelling and loss of freshness. However, excessive surface moisture and condensation can encourage microbial growth. High RH can also lead to sprouting in case of potato, onion and garlic.

Air circulation: Uniform movement of cold air helps maintain a consistent temperature throughout the storage room and prevents non-uniformity in cooling.

Modern cold storage facilities increasingly use advanced refrigeration, automated sensors, data loggers and remote monitoring systems. An important advancement is precooling, which rapidly removes field heat from harvested produce, thereby reducing respiration and slowing quality deterioration. IoT-based systems further enable continuous monitoring of temperature, humidity and other storage conditions, with alerts facilitating timely corrective actions.

Major limitations: Refrigeration slows but does not completely stop deterioration. Moreover, excessively low temperatures can cause chilling injury in sensitive tropical and subtropical commodities. High energy requirements also highlight the need for energy-efficient cooling systems, renewable energy integration and environmentally friendly refrigerants (Hoffmann *et al*., 2025).

Modified Atmosphere Packaging (MAP)

Have you ever noticed that strawberries, fresh-cut vegetables, mushrooms and salad leaves are often sold in sealed plastic packages? These packages are not simply designed to improve appearance or prevent physical damage. Many are specially developed to create a favourable atmosphere around the produce. This technology is known as Modified Atmosphere Packaging (MAP). The basic idea behind MAP is to modify the composition of gases surrounding fresh produce inside a package, particularly oxygen (O_2) and carbon dioxide (CO_2), to slow down respiration and deterioration. Under normal atmospheric conditions, air contains approximately 21% oxygen and 0.04% carbon dioxide. In MAP, the gas composition inside the package is altered to create conditions that are more favourable for maintaining produce quality. When fresh commodities are enclosed in specially selected packaging materials, the gases inside the package gradually change. The packaging film plays a crucial role because it allows gases to pass through at different rates.

- Oxygen enters the package through the film while being consumed by the produce.
- Carbon dioxide is produced through respiration and moves out through the film.
- The balance between gas movement through the film and the respiratory activity of the produce determines the atmosphere inside the package.

When properly designed, this balance creates an environment with reduced oxygen and moderately increased carbon dioxide. Such conditions slow respiration, delay ripening and help maintain freshness. However, the gas composition must be carefully adjusted according to the commodity. Excessively low oxygen can cause anaerobic respiration, resulting in undesirable fermentation, off-flavours and tissue injury. Similarly, excessive carbon dioxide can damage sensitive produce.

Two major approaches to MAP

1. Passive MAP: Produce is packed in a suitable film without initially introducing a specially prepared gas mixture. The natural respiration of the produce and the permeability of the packaging material gradually establish the modified atmosphere.

2. Active MAP: The air inside the package is replaced with a selected gas mixture, generally containing appropriate proportions of oxygen, carbon dioxide and nitrogen. This helps establish the desired atmosphere more rapidly.

A major advantage of MAP is its ability to maintain a favourable atmosphere around produce without requiring specialised storage chambers. It is particularly useful for fresh-cut fruits and vegetables, where cutting accelerates respiration and increases susceptibility to microbial contamination and enzymatic browning. Recent developments include biodegradable films, bio-based polymers, intelligent indicators and sensors for monitoring package conditions and freshness. However, MAP cannot replace refrigeration, as maintaining the cold chain is essential for preserving quality and ensuring food safety. While MAP is

primarily used for packaging and distribution, controlled atmosphere (CA) storage regulates atmospheric conditions within dedicated storage chambers (Fang & Wakisaka, 2021; Zahid *et al*., 2025).

Controlled Atmosphere (CA) Storage

Imagine storing thousands of tonnes of apples in a large refrigerated room for several months without allowing them to ripen rapidly. Ordinary refrigeration alone may not be sufficient to achieve this objective. This is where Controlled Atmosphere (CA) storage becomes important. CA storage is an advanced preservation technology in which the temperature, relative humidity and concentrations of oxygen and carbon dioxide are carefully regulated inside a sealed storage chamber. The principle is based on the fact that oxygen is essential for normal aerobic respiration. By reducing the oxygen concentration to an appropriate level, the respiratory activity of fruits can be slowed considerably. Similarly, increasing carbon dioxide within commodity-specific safe limits can suppress certain physiological processes associated with ripening and deterioration. Together, these changes help delay rapid fruit ripening, softening and loss of firmness, and consumption of organic acids and sugars. For example, apples are among the most commercially important commodities stored under controlled atmosphere conditions. By maintaining suitable low-oxygen and elevated-carbon dioxide conditions along with refrigeration, their marketable quality can be retained for several months, depending on the cultivar, maturity, storage regime and initial fruit quality. Modern CA storage facilities use specialised equipment to regulate the gas composition inside the storage chamber (Bodbodak *et al*., 2016).

- Oxygen control systems reduce oxygen to the desired concentration.
- Carbon dioxide scrubbers remove excess carbon dioxide generated during respiration.
- Nitrogen generators can help establish low-oxygen conditions.
- Gas analysers continuously monitor oxygen and carbon dioxide concentrations.
- Automated control systems regulate gas composition according to predetermined storage requirements.

The storage chamber is also designed to minimise gas leakage so that the desired atmosphere can be maintained.

From conventional CA to Ultra-Low Oxygen storage

One important advancement in CA technology is the development of Ultra-Low Oxygen (ULO) storage. As the name suggests, ULO storage operates at lower oxygen concentrations than conventional CA storage. The objective is to further reduce fruit respiration and delay quality deterioration. However, there is a limit to how much oxygen can be reduced safely. If oxygen becomes too low, fruits may shift towards anaerobic respiration, leading to ethanol and acetaldehyde accumulation, off-flavours and physiological damage. Therefore, the success of CA and ULO storage depends on maintaining the right balance between slowing respiration and ensuring that fruits continue to receive sufficient oxygen for normal metabolic activity. This limitation led researchers to develop an even more sophisticated technology called Dynamic Controlled Atmosphere storage.

Dynamic Controlled Atmosphere (DCA): When storage technology starts listening to the fruit

Conventional CA storage maintains oxygen and carbon dioxide concentrations at predetermined levels throughout storage. Although these conditions are carefully selected for each commodity, the physiological condition of fruits can change during prolonged storage. For instance, two batches of apples may respond differently to the same oxygen concentration because of differences in cultivar, maturity, harvest conditions and physiological condition. This raises an important question: Should storage conditions remain fixed even when the fruits themselves are changing? DCA technology addresses this challenge by continuously monitoring the physiological responses of stored fruits and adjusting the storage atmosphere accordingly. The central principle of DCA is to maintain oxygen at a sufficiently low level to slow fruit metabolism while avoiding oxygen deficiency and the development of anaerobic

conditions. In simple terms, the technology tries to find the lowest safe oxygen concentration that the stored fruits can tolerate without experiencing significant stress or injury. This is particularly important because oxygen requirements are not necessarily identical for every fruit batch or throughout the entire storage period. DCA systems use specialised sensors to detect changes in fruit physiology. Based on these measurements, the oxygen concentration inside the storage chamber can be adjusted automatically.

The technologies that help DCA understand fruits

Three important approaches are commonly used to monitor fruit responses during DCA storage.

Chlorophyll fluorescence (CF): Chlorophyll fluorescence monitoring measures changes in the light emitted by chlorophyll after illumination. It provides information about the functioning of the photosynthetic apparatus in green fruit tissues. As oxygen becomes excessively limited, changes in fluorescence signals can indicate that the fruit is experiencing physiological stress. The system can then increase oxygen availability to prevent injury.

Ethanol monitoring: When oxygen becomes insufficient, fruits may increasingly shift from normal aerobic respiration towards fermentation. Ethanol is one of the products formed during this process. By monitoring ethanol accumulation in the storage environment, DCA systems can identify indications of excessive oxygen limitation and adjust the atmosphere accordingly.

Respiratory quotient (RQ): The respiratory quotient is the ratio of CO_2 released to O_2 consumed during respiration. Under normal aerobic respiration, this ratio generally reflects the type of respiratory substrate being used. A rise in RQ under oxygen-limited conditions can indicate a transition towards fermentation. Monitoring changes in RQ therefore provides another means of identifying when fruits are approaching their oxygen tolerance limit. These approaches provide different ways of identifying physiological stress. Their suitability depends on the commodity, sensor design and storage conditions (Thewes *et al*., 2021).

The biggest advantage of DCA is its ability to move beyond fixed storage conditions towards adaptive storage management. DCA is particularly valuable for long-term storage of apples and has also been investigated for other commodities, including pears and kiwifruit. Its commercial application and effectiveness depend on the commodity and the monitoring system used. Importantly, DCA does not mean continuously reducing oxygen without limits. Rather, it involves identifying and respecting the physiological limits of the produce.

Table 1: Comparison among the technologies

Technology	What is controlled?	How does it work?	Typical application
Cold storage	Temperature and humidity	Slows respiration, moisture loss and microbial growth	Fruits and vegetables during storage and distribution
MAP	Gas composition inside a package	Uses packaging-film properties and produce respiration to establish a modified atmosphere	Fresh-cut produce, berries, leafy vegetables
CA storage	Temperature, humidity, O_2 and CO_2	Maintains a predetermined gas composition inside a sealed room	Long-term storage of apples and pears
DCA storage	Temperature, humidity, O_2 and CO_2, adjusted using physiological monitoring	Uses sensors to detect fruit responses and adapt oxygen levels	Advanced long-term storage, particularly apples and pears

Why do these advancements matter for India?

India is one of the world's leading producers of fruits and vegetables. However, maintaining their quality after harvest remains a significant challenge because of the highly perishable nature of horticultural commodities, inadequate cold-chain infrastructure in some production regions, fragmented supply chains and fluctuations in market demand. The adoption of modern storage technologies can create several opportunities:

- **For farmers:** Reduced postharvest losses and greater flexibility in deciding when to sell their produce.
- **For traders and exporters:** Improved quality retention during transportation and extended market availability.
- **For consumers:** Better access to fresh, nutritious and good-quality produce
- **For the food industry:** A more reliable supply of raw materials for processing and value addition.
- **For the environment:** Reduced food waste and more efficient utilisation of agricultural resources.

However, the adoption of advanced technologies should be guided by the economic value of the commodity, infrastructure availability, electricity requirements, technical expertise and market demand. For instance, large-scale CA and DCA facilities may be economically attractive for high-value fruits such as apples, while affordable MAP solutions and decentralised cold rooms may be more practical for several highly perishable fruits and vegetables. Therefore, the future of postharvest management in India should focus not only on adopting sophisticated technologies but also on making appropriate storage solutions accessible, affordable and sustainable.

Conclusion

The journey of postharvest storage has evolved considerably, from simple refrigeration to sophisticated systems that regulate the atmosphere and monitor the physiological condition of fruits and vegetables. Cold storage laid the foundation by slowing down the natural processes responsible for deterioration. MAP introduced the possibility of creating a protective atmosphere within individual packages. CA storage advanced this concept by allowing precise control of the gaseous environment inside large storage chambers. DCA took the technology a step further by introducing physiological monitoring and adaptive control. These developments represent an important shift in how we approach postharvest preservation. We are gradually moving away from simply storing fruits and vegetables under fixed environmental conditions towards creating storage environments that respond to the needs of the produce itself. Ultimately, the goal is not merely to keep fruits and vegetables in storage for longer periods. It is to ensure that they reach consumers with their freshness, nutritional value, flavour and quality as intact as possible.

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