

# Cold Chain: The Missing Link Between Harvest and Consumer

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## Abstract

freshly harvested fruit or vegetable is still alive. It continues to respire, lose water and respond to its surroundings, and its quality can change rapidly when temperature is not properly managed. The cold chain is therefore much more than a cold room or a refrigerated truck. It is a connected sequence of operations from pre-cooling, storage, packing, transportation and retail handling that keeps produce within suitable conditions until it reaches the consumer. In recent years, this traditional system has begun to change. Sensors can now record temperature and humidity continuously; Internet of Things (IoT) platforms can transmit information in real time; artificial intelligence (AI) can interpret temperature history and estimate remaining shelf life; and computer vision, gas sensors, digital twins and smart packaging can provide additional information about produce condition. There is a need for energy-efficient and intelligent cold storage, while improved pre-cooling and the integration of AI and new-energy technologies would enhance cold storages. These developments point towards a practical change in post-harvest management and better shelf life of agricultural produces.

**Keywords:** cold chain; pre-cooling; post-harvest management; IoT; artificial intelligence; refrigerated transport; smart storage; shelf life

## Introduction

There is a familiar picture in horticulture that a crop is harvested in good condition, carefully packed and sent to market. Yet somewhere between the farm and the consumer, quality begins to disappear. The produce may spend too long in the field after harvest, enter a store before field heat is removed, travel in a vehicle with poor temperature control or remain for hours on a retail shelf without adequate cooling. By the time it reaches the consumer, the loss may be visible as wilting, shrivelling, softening, browning, decay or simply a shorter shelf life.

This is why the cold chain deserves to be viewed as a central part of post-harvest technology rather than as a supporting facility. FAO, (2026) has emphasized that inadequate refrigeration, temperature monitoring and storage infrastructure are important contributors to food loss. The challenge is particularly relevant to fruits and vegetables because they are living, highly perishable commodities and because their quality depends strongly on how quickly and consistently, they are cooled after harvest.

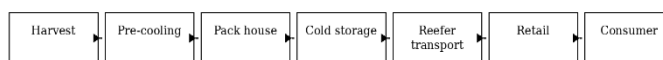
## The Cold Chain Begins at Harvest

Cooling cannot repair every form of damage that occurs before storage. Produce should therefore be harvested

at the appropriate maturity, handled gently and moved to a suitable cooling facility without unnecessary delay. The first few hours after harvest are often decisive because field heat and high respiration can accelerate quality loss.

Pre-cooling is the deliberate removal of field heat before longer-term storage or refrigerated transport. Room cooling, forced-air cooling, hydrocooling, vacuum cooling and ice cooling are among the methods used for different commodities. The correct method depends on crop characteristics, package design, water sensitivity, scale and available infrastructure.

Dai *et al.* (2025), in their review of post-harvest pre-cooling, highlighted the importance of cooling uniformity and airflow behaviour. They also pointed to computational tools such as CFD and to the potential of combining pre-cooling with AI and new-energy technologies. Their message is important: the objective is not simply to cool produce, but to cool it efficiently and uniformly.



**Figure 1.**The cold chain is a sequence of linked operations; a weakness at one stage can affect quality at the next.

## Why Temperature Alone Is Not Enough

Cold store is successful when its display shows the correct temperature. Relative humidity affects water loss, airflow affects cooling uniformity, package arrangement affects heat transfer, and storage duration changes the significance of every temperature exposure.

Hoffmann *et al.* (2025) identified non-uniform cooling, energy-intensive refrigeration and environmental concerns among the major challenges facing post-harvest cold storage. They emphasized intelligent monitoring and improved system design so that refrigeration can respond to actual storage conditions rather than operate only through fixed settings.

This is especially important for mixed-commodity facilities. Apples, mangoes, bananas, leafy vegetables and berries do not have identical requirements. A useful cold chain must therefore be commodity-specific, with suitable temperature, humidity and atmospheric conditions rather than one setting applied to everything.

## Controlled and Modified Atmospheres: Working with the Produce

Temperature management can be strengthened by managing the atmosphere around the commodity. Controlled Atmosphere (CA) storage adjusts oxygen and carbon dioxide

concentrations in the storage room, whereas Modified Atmosphere Packaging (MAP) creates a modified gaseous environment inside a package. For suitable commodities, these approaches can slow respiration and delay some aspects of quality deterioration.

The important point is balance. Too little oxygen or too much carbon dioxide can also injure produce. Atmosphere management therefore has to be designed for the commodity, cultivar, maturity and storage temperature. Future systems are likely to combine gas measurements with temperature and humidity data so that storage conditions can be adjusted more precisely.

### The Journey Outside the Cold Room

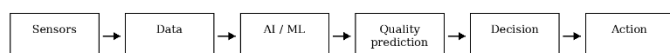
One of the most vulnerable stages of the cold chain is transportation. A refrigerated vehicle may have a powerful cooling unit and still deliver poor results if produce is loaded while hot, packages block airflow, doors are opened repeatedly or the vehicle is overloaded. The temperature displayed by the refrigeration unit may also differ from the temperature actually experienced by produce inside the load.

Continuous data logging provides a more realistic picture. Instead of recording only the set point, sensors can capture the temperature history of the shipment. That history can later be used to understand why quality changed and, increasingly, to predict what may happen next.

### From Cold Chain to Smart Cold Chain

The change is possible because information can now travel with the produce. Small sensors can record temperature and humidity, GPS can provide location; gas sensors can provide information about ripening, cameras can inspect appearance and cloud platforms can bring these observations together. The result is a cold chain that can be observed continuously rather than checked only at selected points.

**The smart cold chain: turning observations into decisions**



**Fig. 2. In a smart cold chain, sensor observations are converted into predictions and management decisions.**

### IoT: Connecting the Physical and Digital Cold Chain

The Internet of Things gives the cold chain a way to 'communicate'. Sensors installed in cold rooms, transport vehicles or packages can send information to a central platform. Operators can receive an alert when temperature rises, humidity moves outside the target range, a door remains open or equipment behaves abnormally.

The real value of IoT is not simply collecting more numbers. It is reducing the time between a problem occurring and someone responding to it. A temperature excursion discovered after a truck reaches its destination is mainly a record. The same excursion detected during transport can become an opportunity for corrective action.

### Artificial Intelligence: Predicting What the Produce Will Become

Fresh produce does not have a single fixed shelf life. Two lots harvested on the same day may reach the market in different conditions because their maturity, initial quality and temperature histories differ. This is where AI and machine learning can be useful.

Elashmawy *et al.* (2025) demonstrated a sensor-driven digital cold-chain approach for strawberries in which initial quality and time-temperature information were used to predict marketability and quality attributes such as colour, sweetness and firmness. The study illustrates an important shift: shelf life can be treated as a changing prediction rather than simply a number printed on a schedule.

Such prediction can support FEFO (first-expired-first-out) where the lots expected to lose marketability sooner are prioritized for sale. In a large distribution system, this could reduce unnecessary storage and help prevent a situation in which older, more vulnerable produce remains behind newer stock.

### Machine Vision: Seeing Quality Without Cutting the Produce

Human inspection remains important, but it can be slow and subjective when thousands of fruits or vegetables need to be assessed. Computer vision can examine colour, size, shape, surface defects, bruising and visible decay at high speed. Hyperspectral imaging can provide additional spectral information that may relate to internal or biochemical changes.

Zhong *et al.* (2023) identified computer vision, smart indicators, sensors, IoT and cloud-based data systems as important components of intelligent fresh-produce supply chains. The attraction is clear: inspection can become faster and less destructive, while the information can be connected to the rest of the cold-chain record.

### Gas Sensors and the Invisible Signals of Ripening

Fruits release gases and volatile compounds as their physiological state changes. Ethylene is particularly important in the ripening of many climacteric fruits. Emerging flexible gas-sensing systems can monitor changes in the surrounding atmosphere and provide another window into ripeness and freshness.

The more interesting possibility is integration. A sensor that detects a change in gas concentration becomes more useful when the system also knows the temperature history and maturity of the fruit. Together, these measurements may allow the cold chain to distinguish between produce that is simply warm and produce whose biological ripening is already accelerating.

### Digital Twins: A Virtual Cold Chain

A digital twin is a digital representation of a physical system that is updated using real-world data. In post-harvest

management, the physical system could be a cold room, a reefer truck, a pallet or even a complete distribution network. Hoffmann *et al.* (2025) highlighted digital twins as an emerging technology for advanced cold-storage management. A digital twin could help answer 'what-if' questions before an action is taken. For example, it could estimate the effect of a delay, a temperature increase or a change in destination on the remaining quality of a shipment. That makes the system more predictive and less dependent on reacting after losses have already occurred.

**Smart Packaging: The Package Can Carry Information Too**

Packaging is no longer only a barrier against physical damage. Time-temperature indicators, freshness indicators, RFID tags, QR-based traceability and gas-sensitive labels can add information about what has happened to a product. In the future, package-level information could be connected directly to warehouse and transport databases. Chang *et al.* (2025) reviewed AI-driven post-harvest quality control and highlighted intelligent packaging as one of the areas in which digital technologies can support quality and safety management. The important consideration is practicality: a smart label is valuable when the information it provides leads to a better decision.

**Blockchain and Traceability**

A cold chain produces a long trail of events—harvest, cooling, packing, storage, transport, arrival and sale. Traceability technologies can organise these records so that the history of a consignment is easier to follow. Blockchain can be used as a distributed record system, while IoT sensors can provide the physical measurements behind the record. Zhong *et al.* (2023) discussed IoT, blockchain and cloud platforms as components of data-driven supply-chain management. However, technology should not be adopted simply because it is fashionable. The quality of the final traceability system still depends on the accuracy of the original data and on whether different systems can communicate with one another.

**Cold Does Not Have to Mean Wasteful Energy Use**

There is an important environmental balance in cold-chain development. Refrigeration can reduce food loss, but refrigeration itself requires energy. A cold chain that saves produce while wasting large amounts of electricity is not the ideal long-term solution. Hoffmann *et al.* (2025) identified energy demand and environmental concerns as major issues and highlighted energy-efficient refrigeration, intelligent monitoring, renewable energy and sustainable refrigerants as future directions. Better insulation, efficient fans and compressors, improved airflow and data-based control can all help reduce avoidable energy use.

**Solar Cooling and Thermal Energy Storage**

For rural and remote locations, solar-powered cold rooms offer a practical opportunity where grid electricity is

unreliable or expensive. Thermal energy storage can store cooling capacity and make better use of available electricity, including renewable electricity generated during the day. The appropriate solution will depend on crop, scale, climate, electricity availability and investment capacity. The aim should be to build a system that remains reliable in the real conditions of the production area, not simply to install the most advanced equipment available.

**Predictive Maintenance: Fixing the Problem Before the Breakdown**

A refrigeration failure can turn a valuable consignment into a loss within a short period. Predictive maintenance attempts to reduce this risk by monitoring equipment behaviour and identifying early signs of abnormal operation. Changes in temperature, vibration, power consumption or compressor behaviour can provide warning signals. Hoffmann *et al.* (2025) identified AI-driven predictive maintenance as an important opportunity for modern cold storage. In simple terms, the system should tell the operator that a machine is beginning to behave differently before the operator discovers the problem through a complete breakdown.

**Table 1. Technologies and Their Role in a Modern Cold Chain**

| Technology              | What it does                                | Why it matters                             |
|-------------------------|---------------------------------------------|--------------------------------------------|
| Pre-cooling             | Removes field heat                          | Protects quality from the beginning        |
| IoT sensors             | Continuously measure conditions             | Provides real-time visibility              |
| AI / ML                 | Analyses sensor and quality data            | Supports shelf-life prediction             |
| Computer vision         | Assesses visual quality                     | Fast, non-destructive inspection           |
| Gas sensors             | Detect changes in gases / volatiles         | Adds information on ripening and freshness |
| Digital twins           | Replicate and simulate physical systems     | Supports prediction and planning           |
| Smart packaging         | Records or communications product condition | Carries information about the product      |
| Predictive maintenance  | Detects equipment anomalies                 | Reduces unexpected cooling failures        |
| Solar / thermal storage | Supports energy-resilient cooling           | Can reduce dependence on grid electricity  |

## What Recent Researchers Recommend

Recent research does not point towards one 'magic' cold-chain technology. Instead, researchers increasingly recommend connecting several technologies so that each solves a different part of the post-harvest problem.

**Table 2. Researcher Recommendations for the Future Cold Chain**

| Researcher(s)                  | Recommendation / key contribution                                                                                          |
|--------------------------------|----------------------------------------------------------------------------------------------------------------------------|
| Dai <i>et al.</i> (2025)       | Improve pre-cooling uniformity and efficiency; combine computational analysis, AI and new-energy approaches.               |
| Hoffmann <i>et al.</i> (2025)  | Develop energy-efficient intelligent cold storage using IoT, predictive maintenance and digital twins.                     |
| Elashmawy <i>et al.</i> (2025) | Use sensor and time-temperature histories with AI to predict marketability and quality dynamically.                        |
| Zhong <i>et al.</i> (2023)     | Integrate sensors, smart indicators, computer vision, IoT, cloud systems and blockchain for intelligent monitoring.        |
| Chang <i>et al.</i> (2025)     | Expand AI for quality inspection, safety, intelligent packaging and automation while addressing data and cost limitations. |

## The Indian Perspective

For India, the cold chain is not only a technology question; it is also an infrastructure and management question. A farmer needs access to suitable collection and pre-cooling facilities, a pack house needs reliable cold storage, and the transport system needs to maintain conditions until the produce reaches the market. The National Horticulture Board, Ministry of Food Processing Industries and National Centre for Cold-chain Development have important roles in developing standards, infrastructure and integrated cold-chain systems.

The Indian situation also shows why technology should be chosen according to scale. A large export-oriented pack house may benefit from computer vision, automated grading and AI-based shelf-life prediction. A small producer may gain more from a low-cost temperature logger, an efficient pre-cooling unit and a mobile alert system. Both are examples of smart cold-chain development if the technology solves a real problem.

## Challenges That Still Need Attention

The future cold chain will not be built simply by adding sensors. Equipment costs, electricity availability, maintenance, skilled manpower and data connectivity can limit adoption. AI models also require large and reliable datasets, and a model developed for one commodity may not perform equally well for another. Chang *et al.* (2025) identified data quality, model interpretability, cost-effectiveness and integration as continuing challenges. Interoperability is another practical issue. A sensor installed by one company may generate data in a format that another platform cannot easily use. If farmers, transporters, warehouses, processors and retailers cannot share information, the full value of a connected cold chain is lost. For this reason, future progress should focus not only on more advanced hardware, but also on simple interfaces, common data standards, training, maintenance and affordable deployment.

## From a Cold Chain to a Quality Chain

Consider a shipment of mangoes leaving a farm. The produce is harvested, quickly pre-cooled and packed. A sensor records temperature and humidity during transport. A camera checks external quality. The system combines these observations with the maturity and temperature history of the lot. An AI model estimates remaining marketable life. If one batch is likely to ripen earlier, it can be sent to a nearby market while a more stable batch can travel farther. This example shows where the cold chain is heading. The purpose is not simply to keep every box at one temperature. The purpose is to understand the condition of each consignment and make better decisions before quality is lost.

## Implications for Farmers, Industry and Consumers

For farmers, a reliable cold chain can reduce deterioration and create opportunities to reach markets farther from the production area. For processors and retailers, better monitoring can improve inventory management, traceability and quality control. For consumers, the result can be fresher produce with a more predictable quality at the point of purchase.

There is also a wider environmental benefit. When food is saved after harvest, the land, water, labour and energy already used to produce that food are not wasted unnecessarily. At the same time, refrigeration systems themselves need to become more efficient. The future therefore lies in reducing both food loss and avoidable energy consumption.

## Conclusion

The quality of horticultural produce is decided by more than what happens in the field. Harvest timing, handling, pre-cooling, storage, transport and retail conditions all shape what finally reaches the consumer. Among these stages, the cold chain acts as the link that holds the system together.

Research is now taking the cold chain beyond conventional refrigeration. Sensors can show what is happening, IoT can

communicate it, AI can interpret it, computer vision can inspect it, gas sensors can reveal physiological changes, digital twins can simulate it and smart packaging can carry information with the product. At the same time, solar energy, thermal storage, efficient refrigeration and predictive maintenance can make the system more sustainable and reliable. The recommendations emerging from recent studies are consistent: cooling should become more uniform, monitoring should become more continuous, decisions should become more data-driven and energy use should become more efficient. The future cold chain should therefore not be judged only by how cold it keeps produce, but by how well it preserves quality from harvest to consumer. In that sense, the cold chain is not merely a storage technology, it is the missing link that protects the value created on the farm.

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