

# YOUR VIRTUAL COLD

## OPERATORS MANUAL



# CHAIN ASSISTANT

Credit: Cold Room Operator in Muzaffarpur, India/  
Oorja Development Solutions Ltd.



# PREPARED IN COOPERATION WITH:

COOLCROP TECHNOLOGIES PRIVATE LIMITED,  
COLDHUBS LIMITED, KOEL FRESH PRIVATE LIMITED,  
AND OORJA DEVELOPMENT SOLUTIONS LIMITED.



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# INDEX

<b>ABOUT THE MANUAL</b>	<b>05</b>
<b>ACKNOWLEDGEMENTS</b>	<b>06</b>
<b>CHAPTER 1: INTRODUCTION TO COLD CHAINS FOR THE FRESH PRODUCE INDUSTRY</b>	<b>07</b>
1.1 THE PROBLEM OF POST-HARVEST LOSSES	08
1.2 CHALLENGES IN COLD CHAIN DEVELOPMENT: HIGH-INCOME VS. LOW- AND MIDDLE-INCOME COUNTRIES	08
1.3 TYPES OF COOLING TECHNOLOGIES	10
1.3.1 ACTIVE COOLING	10
1.3.2 PASSIVE COOLING	11
1.4 WHAT IS THE DIFFERENCE BETWEEN CENTRALISED AND DECENTRALISED COOLING?	13
1.4.1 CENTRALISED COLD ROOMS	13
1.4.2 DECENTRALISED COLD ROOMS	14
1.5 SUSTAINABILITY BENEFITS OF SOLAR-POWERED, DECENTRALISED COLD ROOMS	14
<b>CHAPTER 2: POST-HARVEST HANDLING AND TREATING METHODS</b>	<b>17</b>
2.1 STAGES OF POST-HARVEST HANDLING	18
2.2 FACTORS INFLUENCING CROP QUALITY AT THE POST-HARVEST LEVEL	19
2.3 HOW FAST DO FRUITS AND VEGETABLES COOL?	20
2.4 WHERE SHOULD YOU PLACE SENSORS IN THE COLD ROOM?	21
2.5 WHAT ARE THE BEST PRACTICES TO MANAGE MULTI-COMMODITY COLD ROOMS?	22
2.6 HOW IS THE POST-HARVEST LIFETIME OF CROPS DETERMINED?	24
2.7 HOW DO THE GASES IN THE ROOM AFFECT THE STORAGE LIFE OF THE PRODUCT?	26
2.8 WHAT IS SORTING, AND WHY IS IT IMPORTANT?	27

2.9	WHAT DOES GRADING MEAN, AND WHY IS IT IMPORTANT?	28
2.10.	WHAT ARE THE BEST METHODS TO PACKAGE THE CROPS, IN PARTICULAR WITH REGARD TO HYGIENE AND LIFETIME?	28
<b>CHAPTER 3: RUNNING COLD ROOMS USING SERVITISATION AND DIGITALISATION</b>		<b>29</b>
3.1	WHAT IS COOLING-AS-A-SERVICE?	30
	3.1.1 THE PROBLEM: MARKET BARRIERS	30
	3.1.2 THE SOLUTION: BUSINESS MODEL INNOVATION	30
	3.1.3 KEY STAKEHOLDERS INVOLVED	31
3.2	DIGITAL INNOVATION	32
	3.2.1 WHAT ARE THE FEATURES OF COLDTIVATE?	32
	3.2.2 HOW CAN THE THREE STAKEHOLDERS – FARMERS, COLD ROOM OPERATORS, AND COOLING COMPANIES – USE COLDTIVATE?	32
3.3	DIVIDING OPERATIONAL ROLES AND RESPONSIBILITIES UNDER CAAS	33
3.4	MANAGING COLD ROOM OPERATIONS UNDER CAAS	36
	3.4.1 CHECKLIST FOR COLD ROOM SITE SELECTION	36
	3.4.2 TIPS TO ONBOARD NEW USERS	36
	3.4.3 TIPS FOR CHECKING-IN CRATES	37
<b>CHAPTER 4: MAINTAINING SOLAR-POWERED COLD ROOMS</b>		<b>45</b>
4.1	TIPS FOR MAINTAINING DIFFERENT PARTS OF THE COLD ROOM	46
4.2	EMERGENCY RESPONSE TO TECHNICAL DIFFICULTIES IN THE COLD STORAGE	48
<b>CHAPTER 5: HOW CAN YOU START USING COLDTIVATE?</b>		<b>49</b>
5.1	HOW CAN YOU JOIN COLDTIVATE?	50
5.2	WHAT ARE THE MAIN FUNCTIONALITIES OF COLDTIVATE?	51
5.3	COLDTIVATE'S STORAGE LIFE MODEL	55
<b>REFERENCES CHAPTER 1</b>		<b>58</b>
<b>REFERENCES CHAPTER 2</b>		<b>59</b>
<b>REFERENCES CHAPTER 3</b>		<b>60</b>

# ABOUT THE MANUAL

The global food supply faces challenges in meeting demand, primarily due to deficiencies in distribution systems and significant post-harvest losses, particularly in developing countries. According to the FAO, despite producing 1.5 times the amount of food needed worldwide, approximately one-third of global production is lost throughout the value chain. In low- and middle-income countries, food loss predominantly happens on farms and during distribution. Insufficient cold storage capacity, the absence of standards, and inadequate technology tailored to smallholder farmers exacerbate the issue. Addressing these challenges not only improves food security but also reduces poverty. **One potential solution is the promotion of decentralised and multi-commodity cold rooms strategically located near farms and markets. Operating under the Cooling-as-a-Service business model, these rooms would be more accessible to farmers and accommodate multi-cropping farming patterns.**

This manual provides a comprehensive guide filled with insights into the fresh produce value chain and practical tips to assist cold room operators in managing solar-powered cold rooms that store multiple crops together. By following the guidance in this manual, operators can ensure that smallholder farmers derive maximum value from utilising the cold rooms.

**Chapter 1:** introduces the post-harvest loss problem and presents decentralised cold rooms as a solution. It explores how these innovative facilities can help mitigate the issue and contribute to sustainable development goals.

**Chapter 2:** examines the different phases of the fresh produce value chain. It discusses factors influencing crop quality during the post-harvest stage and provides best practices to optimise storage life based on temperature requirements and ethylene sensitivity.

**Chapter 3:** elaborates on applying the Cooling-as-a-Service business model in the agricultural sector. It describes the operational responsibilities of cooling companies, operators, and community groups such as farmer producer organisations and self-help groups. The chapter introduces Your Virtual Cold Chain Assistant (Your VCCA), a joint project by the Basel Agency for Sustainable Energy and Empa. Your VCCA combines servitisation and digitalisation to build smallholders' trust and benefit from post-harvest cooling. The flagship app, Coldtivate, helps manage cold rooms and monitor the remaining storage life of stored crops, enabling profitable sales decisions. The chapter explains how the app's operational responsibilities are divided among the three user types.

**Chapter 4:** provides troubleshooting measures for technical issues in solar-powered cold rooms.

**Chapter 5:** outlines the main steps for cooling companies, operators, and farmers to begin their Coldtivate journey.

# ACKNOWLEDGEMENTS

This manual is the result of collaboration between interdisciplinary experts from the Basel Agency for Sustainable Energy (BASE) and Empa's Simulating Biological Systems (SimBioSys) group. It incorporates recommendations and firsthand insights from practitioners in the cooling industry who are actively involved in efforts to reduce post-harvest losses and enhance farmer livelihoods.

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## Chapter 01

# INTRODUCTION TO COLD CHAINS FOR THE FRESH PRODUCE INDUSTRY

A food crisis looms large over countries, with 278 million people in Africa, 425 million in Asia and 56.5 million in Latin America and the Caribbean suffering from acute hunger.<sup>1</sup> Post-harvest losses jeopardise livelihoods, food and nutrition security, as well as a significant portion of investments in the agricultural sector aimed at addressing these issues.

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## 1.1 THE PROBLEM OF POST-HARVEST LOSS

Although the Food and Agriculture Organisation (FAO) estimates that the world already produces 1.5 times enough food to feed everyone on the planet, the food supply fails to meet demand due to issues within the systems of food distribution.<sup>2</sup> Globally, approximately one-third, or 1.3 billion tons, of food produced is lost along the value chain, which encompasses the interlinked stages from production to consumption.<sup>3</sup>

In this manual, we focus on preventing food loss within the post-harvest segment of the fresh produce value chain. One major cause of food loss during this phase is the absence of temperature control and a complete cold chain, which is essential for preserving the quantity (weight and volume) and quality (physical characteristics and conditions) of perishable items. A **cold chain** refers to an unbroken flow of perishable products from the point of production through the distribution channels to the final consumer through a temperature-controlled supply chain. As Nicola Twilley elegantly describes it, *“The cold chain is the invisible backbone of our food system, a perpetual mechanical winter that we have built for our food to live in.”*<sup>4</sup>



**23%** of food produced in developing countries is lost due to lack of refrigeration.

Interruptions in such a cold chain cause significant post-harvest loss for perishable produce. Even with conservative estimates, the annual economic loss for farmers worldwide due to post-harvest losses reaches a staggering USD 1 trillion.<sup>5</sup> These losses can also reduce average farmer incomes by 15 percent in comparison to their earnings when food is well-preserved.<sup>6</sup> Thus, the absence or limited access to cold chains not only exacerbates food insecurity but also deepens poverty.

## 1.2 CHALLENGES IN COLD CHAIN DEVELOPMENT: HIGH VS. LOW AND MIDDLE-INCOME COUNTRIES

In 2009, a cross-country analysis by the International Institute of Refrigeration (IIR) found that **developing countries lost 23 percent of the food they produced due to the lack of refrigeration, 2.5 times more than developed countries.**<sup>7</sup> In high-income countries (HIC), food spoilage is primarily concentrated at the consumer level (retail, preparation, cooking, and consumption), rather than occurring within the post-harvest segment of the value chain, which is well-equipped with efficient crop handling and storage systems.<sup>8,9</sup> In contrast, the majority of food spoilage in low and lower-middle-income countries (LMIC) as well as upper-middle-income countries (UMIC) occurs on farms and during the distribution phase due to inadequate storage infrastructure and limited training on appropriate post-harvest management practices.

Prolonging the shelf life of produce by slowing down microbial growth, which is responsible for food spoilage, requires cooling. However, the existing cooling technology in LMICs is often outdated and ineffective in slowing down the decay of perishables that begins soon after production due to an increase in unnecessary heat intake during food handling.\* Currently, in LMICs, there is only 19m<sup>3</sup> of refrigerated storage capacity for every thousand farmers, which is 10.5 times less than what developed countries have. Consequently, many farmers and traders operating in remote areas have had to resort to storing their crops under the shade of trees, in deep wells, and transporting the produce during the night or early morning.<sup>11</sup>

\*Food wastage and losses result from the inherent living nature of food, which remains true even after harvest. After harvest, food undergoes accelerated natural degradation as cells break down without replacement. This vulnerability makes the produce susceptible to microbial attacks it could resist before harvest. Additionally, latent illnesses, dehydration, and other factors contribute to its deterioration.



Beyond poor infrastructure and investments, LMICs face many structural challenges in adopting post-harvest cooling technologies. One significant obstacle is the **intricate multi-stakeholder engagement** within food value chains across most developing nations, which differs from HICs. This distinction is a key factor contributing to the greater success of cold storage investments in HICs, where downstream losses have been effectively reduced to 10 percent. Rural farmers in LMICs often rely on intermediaries for crop sales due to their limited access to market information and integration into distribution networks.<sup>12</sup> Smallholder farmers, reliant on daily income for their livelihoods, typically sell their crops immediately after harvest in local markets or to aggregators. Most times, the prices they receive barely cover their production costs. This results in a pattern of multiple crop exchanges from one aggregator to the next, typically without any value addition, which in turn discourages each stakeholder from investing in cold storage solutions.

Even when accessible to farmers, bulk storage facilities often lack proper cooling due to neglected infrastructure and low grid connectivity. This limitation, combined with the fact that such facilities are frequently located in urban areas, necessitates transportation – a challenge for many smallholder farmers. Therefore, their ability to store crops for extended periods to fetch better off-season prices is curtailed.

Anecdotal evidence suggests that a common concern among farmers in using bulk storage rooms with large capacities is the potential lack of training among cooling unit operators. This includes limited knowledge about

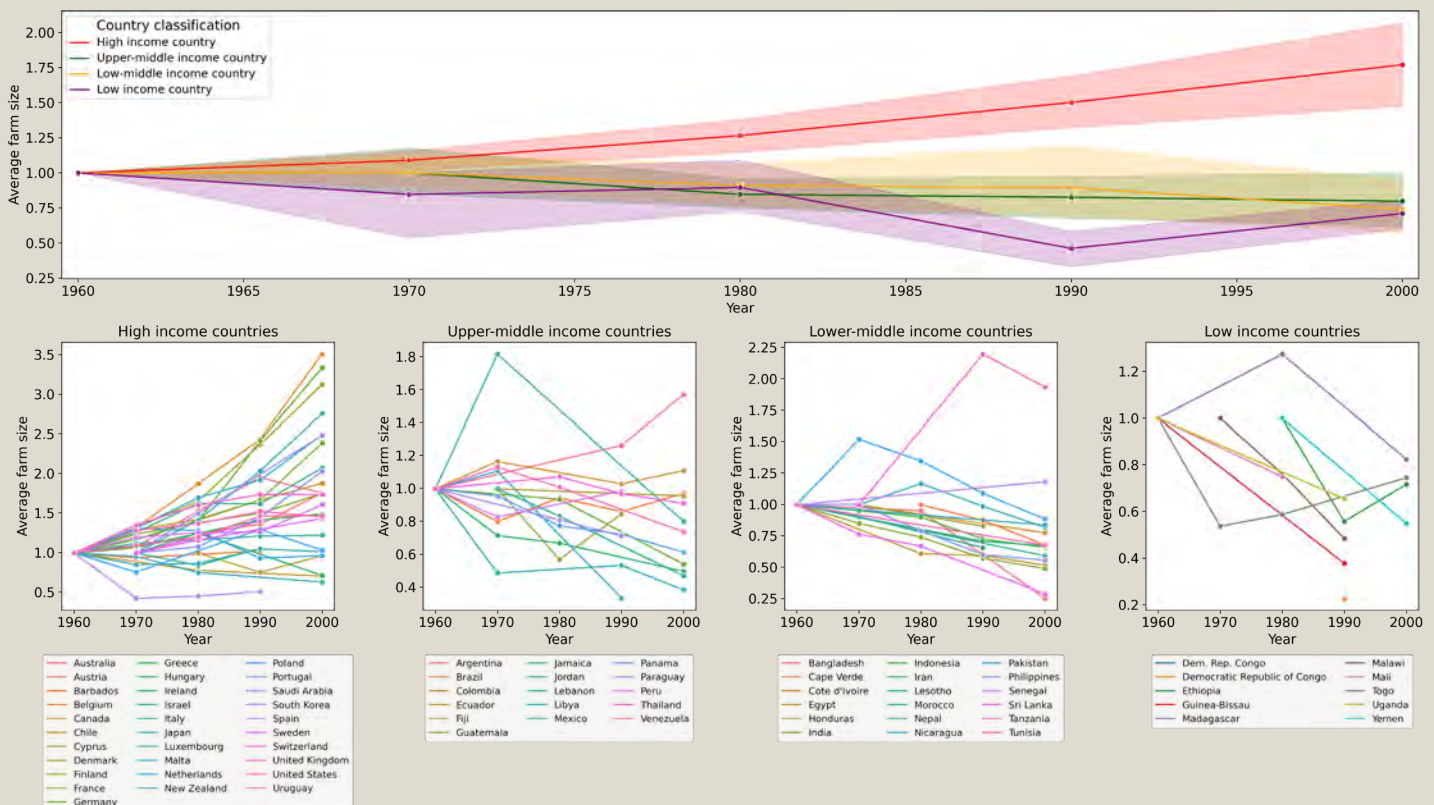
storage best practices and the required temperature ranges for different crop combinations. The absence of established standards for temperature, processing, and packaging worsens the rapid deterioration of produce quality. To make matters worse, such storage rooms are often overcrowded, restricting proper airflow between commodities. The failure to segregate decaying and healthy fruits and vegetables further accelerates the spoilage of even the highest-quality produce.<sup>13</sup> These issues collectively result in farmers deriving limited benefits from investing in cooling solutions. Disillusioned by cooling solutions, farmers have stopped applying significant bottom-up pressure on the government to prioritise the advancement of cold chains.

In the first mile of the food supply chain, smallholder farmers encounter challenges in accessing cutting-edge technologies designed with larger farms in mind. **Figure 1.1** highlights the trend in farm sizes, illustrating HICs' continuous expansion from the 1960s to the early 2000s. In contrast, LMICs and UMICs have seen farm sizes decrease due to land division among heirs. Since most research and development originates from HICs, solutions and technologies tailored to larger farms may not effectively meet the needs of smallholders, if they do so at all.

**INNOVATIVE TECHNOLOGIES AND BUSINESS MODELS MUST MATCH LOCAL COOLING NEEDS AND FARM SIZES TO ENSURE THAT SMALLHOLDERS ARE NOT LEFT BEHIND.**

**Farm size has been drifting apart for decades between LMIC, UMIC vs. HICs**

**Figure 1.1:** Farm sizes in HICs continued to grow while farm sizes in LMICs and UMICs grew smaller between 1960 and 2000.





## 1.3 TYPES OF COOLING TECHNOLOGIES

### 1.3.1 Active cooling

Active cooling is defined as a heat-removing mechanism that consumes energy to extract heat from a controlled and sealed environment using fans and heat pumps. Within the context of post-harvest refrigeration, this controlled environment is called a **cold room** – a large, insulated box with a refrigeration system and a door. The temperature varies in different areas inside the room depending on airflow, the way produce has been loaded inside, and the amount of field heat contained within the stored produce.

**Decentralised active cooling systems** have emerged as popular options in off-grid areas as they are powered by renewable energy from solar photovoltaic panels. In addition to this, the rooms may also require an energy storage system to keep the systems operating at their set temperature during cloudy or rainy days and non-solar hours, which can be achieved either by a **chemical energy storage system (batteries)** or a **thermal energy storage system (TES)**. The batteries store electrical energy to temporarily replace the solar panels during non-solar hours, powering the mechanical systems that generate cold air. In contrast, a TES stores cold energy, which can be later circulated into the room. This process only requires a small additional battery for auxiliary loads to operate the pumps and fans.

In other words, TES functions like a 'cold bank,' storing cold energy in a phase-change material such as water or water eutectic mixtures, such that the cold energy can then be transferred to the cold storage unit when needed. During daylight hours, the solar photovoltaic panels supply power to the refrigeration system, typically through a vapor compression refrigeration cycle. This cycle is used first to cool down the cold room and second to store cooling energy in the TES. As a backup, TES significantly reduces the need for chemical energy storage (i.e. batteries). Adding to its appeal, this solution is both more sustainable and economical. During non-solar hours, the cooling needs of the cold storage unit are satisfied by circulating the stored cooling from the TES throughout the room, rather than generating cold energy using batteries during these times.

Utilising solar photovoltaic panels and a TES backup eliminates the reliance on the grid and the necessity for a diesel generator. The system primarily consists of the following components and equipment: Cold Room, Solar Photovoltaic System, Solar Controller, Refrigeration System, Thermal Energy Storage, and Batteries for Auxiliary Load. Such systems are designed modularly, which means that different configurations and system sizes can be created depending on the need.

### 1.3.2 Passive cooling

Despite the benefits of decentralised solar-powered cold storage, active cooling presents some disadvantages due to its energy-intensive and costly nature. Successful implementation requires a reliable energy supply, appropriate hardware, and skilled personnel for equipment maintenance. In situations where these conditions are not met and innovative business models are not available to assist farmers in managing significant capital and operational expenses, alternative low-tech cooling solutions become essential. These options are especially relevant for farmers in remote off-grid areas with limited financial resources.



Passive cooling is a feasible solution for small-scale farming operations that works in dry, low-humidity areas and does not require electricity. It is capable of maintaining a controlled environment within the temperature range of 10°C to 25°C. However, for its operation, farmers must have access to water. Passive cooling technology is considered one of the top 22 investable innovations that can transform food systems in emerging markets.<sup>14</sup>

This highly promising sustainable cooling solution relies on water evaporation, which cools warm air and creates a humid storage environment. It extracts heat from the air, food, and surrounding materials, thereby inducing cooling. Evaporative cooling effectively slows down thermally-driven food degradation, lowering temperatures by 3 to 10 °C and increasing relative humidity by up to 90 percent, thus reducing moisture loss. These lower temperatures and higher humidities can extend shelf life by 2-6 days. Such evaporative cooling solutions are already in use and have demonstrated global success in passive cooling buildings.

Despite the evident advantages of evaporative cooling solutions, their deployment is infrequent. This is due to the fact that existing evaporative coolers, including clay-based, sand, and brick coolers, demand advanced construction and maintenance skills, often have high initial costs, require materials that are not always locally available, and lack scalability. Consequently, the currently accessible evaporative cooling solutions are not widely adopted by smallholder farmers caught in the cycle of poverty. Keeping these concerns in mind, researchers at the Swiss Federal Laboratories for Materials Science and Technology have developed a **straightforward and cost-effective small-scale passive cooling blanket**.

The charcoal cooling blanket in **Figure 1.2** serves as an illustrative example of passive cooling. It is characterised by ease of scalability, simplicity, self-sufficiency, and cost-effectiveness. This cooling blanket is composed of three key components that contribute to its cooling effect: i) an air-permeable and hydrophilic hessian or jute fabric, ii) charcoal, and iii) water. The textile-based hessian or jute fabric is not only affordable but also readily available from local sources. You can see the steps for constructing a charcoal blanket cooler room in **Figure 1.3**. Moreover, this versatile blanket can be applied across various points in the supply chain.

Figure 1.2: Flowchart on how to construct a charcoal cooler.

**Step 01:** filling a crate with crops and placing temperature and humidity sensors on the crops; **Step 02:** filling the sewed burlap blanket with charcoal; **Step 03:** mounting wooden poles at the farm; **Step 04:** wrapping the charcoal blanket around the mounted poles; **Step 05:** covering the cooler with tarps and watering the charcoal blankets; **Step 06:** placing the filled crate of crops in the charcoal cooler for preservation.<sup>16</sup>

01.



02.



03.



04.



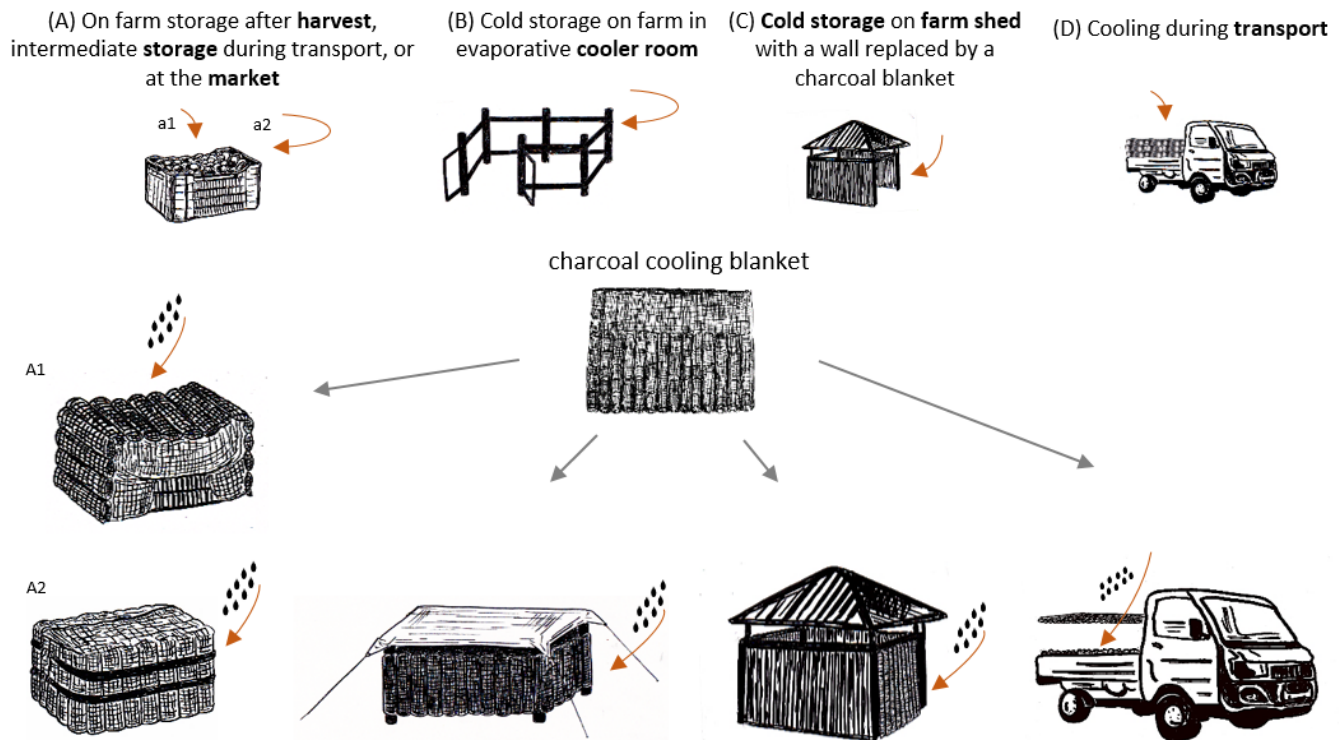
05.



06.



Figure 1.3: Concept illustrations on how and where the charcoal blanket can be applied in different steps of the supply chain, including (a) temporary or intermediate storage at the farm or market, (b) transport, and (c-d) longer-term storage in silos or permanent and makeshift sheds as a replacement wall.<sup>17</sup>



THE SELECTION OF AN APPROPRIATE COLD STORAGE TECHNOLOGY DEPENDS ON FACTORS LIKE THE REQUIRED TEMPERATURE, RELIABILITY, AND THE AVAILABILITY OF RESOURCES SUCH AS SKILLED LABOR, CAPITAL, ELECTRICITY, AND WATER SUPPLY.

## 1.4 WHAT IS THE DIFFERENCE BETWEEN CENTRALISED AND DECENTRALISED COOLING?

### 1.4.1 Centralised cold rooms

Currently, the storage and post-harvest handling of fresh produce in developing countries mainly rely on private and government-owned temperature-controlled urban warehouses. When farmers in rural areas seek access to these facilities, the produce is transported over several miles at ambient temperatures before reaching centralised cold storage facilities. This temperature variation can lead to irreversible damage to the crops due to changes in respiration rates and moisture content, which cannot be remedied by subsequent cooling in centralised storage rooms.

Furthermore, many of these warehouses are designed for storing single commodities, falling short of meeting farmers' demands for multi-commodity storage options. For instance, in India, approximately 64 percent of cold storage rooms have capacities of 1,000 metric tonnes or more. However, a significant majority of these larger facilities, ranging from 80 to 95 percent, are exclusively dedicated to storing potatoes.<sup>18,19</sup>

Centralised cold rooms continue to operate using an energy-intensive process, resulting in high electricity bills even when the storage space is significantly underutilised. The unreliability of the electrical grid necessitates the use of fossil fuel generators as backup power, without which the produce stored in these cold storage facilities can be at risk. Since commercial forms of energy in developing and least developed countries still rely on fossil fuels (coal, oil, and natural gas), the high cost of conventional energy sources and the lack of comparable energy infrastructure in villages and smaller towns have created a rural blind spot in agricultural cooling. In off-grid areas, the deployment of decentralised cold rooms powered by renewable energy sources can help bridge the existing cooling gap. **Section 1.5** explores the benefits of sustainable cooling in reducing food waste and improving farmer livelihoods.

### 1.4.2 Decentralised cold rooms

**Decentralised cold rooms refer to stand-alone cooling chambers, typically with a holding capacity of anywhere between 3 and 50 metric tonnes, placed at the farm gate, local markets, or ideally, both.** Given the absence of stable and reliable electricity, companies have started designing decentralised cooling solutions running on solar mini-grids with energy storage to provide service overnight and as a backup during cloudy days. In some areas, hybrid cold rooms run on a combination of on-grid (connected to the national utility grid) and off-grid solar energy systems. New containerised cooling technologies, coupled with innovative business models (such as Cooling-as-a-Service, discussed in **Chapter 3**), aim to make their widespread deployment economically viable, placing cooling closer to production points to directly benefit local communities.

## 1.5 SUSTAINABILITY BENEFITS OF SOLAR-POWERED, DECENTRALISED COLD ROOMS

Solar-powered decentralised systems contribute to the Sustainable Development Goals (SDGs) and increase access to cold storage for smallholder farmers, as represented in **Figure 1.4**.

### SHORT-TERM GOALS



#### SDG 9: INDUSTRY, INNOVATION AND INFRASTRUCTURE

Decentralised cold rooms demonstrate how reliable and sustainable infrastructure can foster economic development and enhance human well-being by ensuring affordable and equitable access to cooling for all. When operated under a servitisation business model, these decentralised cold rooms relieve

farmers of upfront and operational costs. Cooling can be accessed at nominal rates, where farmers only pay for the amount of produce stored each day. This model creates incentives for the provider to design goods with greater durability, extend product life through repair and remanufacturing, maximise value recovery at the end-of-life, and optimise resource efficiency throughout the entire product life cycle using modular systems that allow for equipment repurposing to adapt to changing end-user requirements. All of these factors contribute to the transition to a circular economy.



#### SDG 7: AFFORDABLE AND CLEAN ENERGY

Rural electrification in developing countries remains particularly low. Due to their small sizes, decentralised cold rooms operate efficiently on solar mini-grids or hybrid systems, often proving to be more cost-effective and environmentally friendly in the long run compared to the utility's power grid. With the increasing threat of climate-related events and extreme weather conditions, electricity disruptions have become more frequent, reducing the reliability of energy supply for centralised cold rooms, which are typically grid-dependent. In contrast to centralised rooms that provide full-space service regardless of occupancy, decentralised cold rooms often function as multiple small units. This setup allows for the full optimisation of each unit's capacity, with units not in operation being switched off to save electricity. Excess solar production can be either injected back into the grid or stored for later use, supporting uninterrupted socioeconomic growth in underserved regions. Most importantly, decentralised cold rooms promote greater social inclusivity and sustainability by making cooling widely accessible and creating local employment opportunities, respectively.



#### SDG 12: RESPONSIBLE CONSUMPTION AND PRODUCTION

Decentralised cold rooms play a crucial role in achieving the goal of reducing food losses throughout the production and supply chains. They enable farmers to extend the shelf life of their crops, ranging from a few days to several months. As against the current scenario, where farmers often have to discard their produce due to inadequate storage, affordable access to cooling services significantly reduces the loss of perishables even before they reach the consumer.

## MEDIUM-TERM GOALS



## SDG 10: REDUCED INEQUALITY WITHIN AND AMONG COUNTRIES

Establishing sustainable infrastructure (**SDG 9**) powered by clean energy (**SDG 7**) can collectively help mitigate the pronounced income inequalities among small and marginal farmer groups, as well as semi- and medium-sized and large farmers. Smallholders, particularly women, often cannot afford to store their crops in centralised cold rooms due to limited financial resources and access to transport. Consequently, smallholders are frequently compelled to sell their crops to intermediaries at below-market rates. Improved access to decentralised cooling allows farmers to retain their crops until just a few days before the market opens. Furthermore, with culturally enforced restrictions on women's mobility, cold rooms located at farms or local markets also **enhance female farmers' access to cooling benefits (SDG 5)**.

Since they no longer have to rely on middlemen to take care of the crops and can store them in decentralised rooms, farmers can negotiate better prices. In some cases, smallholder farmers can join forces to transport their crops to the market themselves and secure fairer prices. Crops sold in bulk through cold storage can fetch competitive rates for farmers. Alternatively, decentralised cold rooms can serve as aggregation centres for customers to directly visit and purchase fresh produce, bringing the point of sale closer to the point of production. Locating cold rooms within villages is also the first step toward increasing access to and building trust in cooling solutions among smallholder farmers, as it allows them to check on their crops frequently.



## SDG 8: DECENT WORK AND ECONOMIC GROWTH

Decentralised cold rooms open doors for the involvement of local communities in running and maintaining the facilities, enabling the adoption of alternative income-generating activities by rural households. The local companies responsible for setting up the cold rooms on a pay-per-use basis can offer targeted guidance for training self-help groups and Farmer Producer Organisations (FPOs) on the operations, customer interactions, and technical aspects. With vested economic interest in the cold rooms and regular check-ups by farmers, the cold room operators are incentivised to ensure immaculate maintenance and services of the room.



## SDG 2: ZERO HUNGER

By helping reduce post-harvest losses, decentralised cold rooms ensure that local and regional markets are supplied with sufficient, safe, and fresh food. The availability of cooling solutions in close proximity allows smallholder and marginal farmers to use short-term storage for crops sold within two to three days of harvest, which would otherwise have to be discarded or abandoned on the streets by the end of the day. In some developing countries, farmers choose to produce agricultural products for which the government offers a minimum support price; access to cold rooms also promotes the production of more horticultural crops, guaranteeing food and nutritional security.

## LONG-TERM GOALS



## SDG 1: NO POVERTY

Commercialising smallholder agriculture through strengthening farmers' negotiating positions, increasing their participation in the agricultural value chain, and facilitating market linkages to points of sale provides them with better financial returns for their hard work.



## SDG 3: GOOD HEALTH AND WELL-BEING

Improved access to fresh food and a reduction in food waste help protect the population against malnutrition and non-communicable diseases caused by improper waste management.



## SDG 13: CLIMATE ACTION

Solar-powered decentralised cold rooms present a climate-resilient and low-carbon alternative to relying on the grid. Electricity disruptions from the grid have increased due to climate change, including heavy rains, cyclones, and storms, resulting in unreliable energy supply, which is often faced by centralised cold rooms. Solar-powered off-grid systems offer a more reliable energy supply. The use of high-energy storage capacity batteries or thermal storage allows for uninterrupted energy supply, even on cloudy days. Additionally, decentralised cold rooms provide immediate and affordable crop protection for rural farmers. Otherwise, they would have to travel long distances to store crops for shelter in centralised cold rooms during extreme weather events, such as heatwaves and floods. Using renewable energy to operate these rooms and reducing food loss also helps to decrease CO<sub>2</sub> emissions. Consequently, decentralised cold rooms enhance agricultural resilience, ensure the efficient use of natural resources, and improve farmer livelihoods.

Figure 1.4: Contribution of Decentralised Cold Storage Solutions to the SDGs



**SHORT-TERM GOALS**

**SDG 09**  
Industry, Innovation and Infrastructure



**SDG 07**  
Affordable and clean energy



**SDG 12**  
Responsible Consumption and Production



**MEDIUM-TERM GOALS**

**SDG 10**  
Reduced Inequality



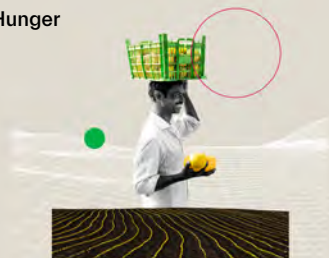
**SDG 05**  
Gender Equality



**SDG 08**  
Decent work and Economic Growth



**SDG 02**  
Zero Hunger



**LONG-TERM GOALS**

**SDG 01**  
No Poverty



**SDG 03**  
Good health and well-being



**SDG 13**  
Climate Action







## Chapter 02

# POST-HARVEST HANDLING AND TREATING METHODS

This chapter will highlight tips on *when* and *how* to harvest, store, sort, grade, and clean crops. It explains the importance of appropriate post-harvest handling practices and treatment methods in maintaining the quality of harvested fruit and extending its shelf life.

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## 2.1 STAGES OF POST-HARVEST HANDLING

**Figure 2.1** provides an overview of a typical post-harvest chain, outlining the various steps involved in moving horticultural crops from farms to consumers. However, the specific chain may vary for each fruit or vegetable based on factors such as the product type, the market destination, and whether it is intended for domestic consumption or export. The subsequent sections will provide a detailed exploration of the various stages in the fresh produce supply chain, which are briefly outlined below:

- i) After the harvest of fruits and vegetables, farmers initiate the process by sorting them to separate the good crops from the spoiled ones.
- ii) The marketable crops are then transported over short distances, either to a packhouse or directly to a cold room. Ideally, refrigerated trucks should be used for transportation, but in many cases, such specialised vehicles are still unavailable. To mitigate quality loss, pre-cooling the crops or transporting them during the early morning or cooler hours can be effective.

iii) At the packhouse, the produce undergoes a series of processes, including re-sorting, washing, and grading (as detailed in **sections 2.8 and 2.9**). Depending on the type of fresh produce, additional treatments may be applied, such as degreening (for citrus fruits), ripening (for bananas), and pre-treatment. Crops may also be pre-cooled, packed, and then stored in a cold room under optimal conditions (refer to **sections 2.3, 2.6, and 2.10**).

iv) After leaving the packhouse, fruits and vegetables are transported to their destinations, which could be nearby retail markets or distant cold rooms. This transportation is facilitated by various means, including refrigerated trucks, trains with refrigerated containers, or even airplanes.

v) Within decentralised cold rooms, crops are subject to re-sorting and are stored in a temperature-controlled environment conducive to preserving their quality.

vi) Ultimately, consumers purchase the produce either from retail markets or directly from local farmers, completing the journey of food from farm to fork.

**Figure 2.1:** A typical post-harvest supply chain of fresh produce from the farm (1) to the consumer (6)

**Step 01:** good quality crops are sorted from the spoiled ones after harvest; **Step 02:** marketable crops are transported to a packhouse if they are destined for the retail market, or to a cold room if farmers intend to sell them at a later time; **Step 03:** crops are re-sorted, washed, and graded at the packhouse; **Step 04:** packaged crops are either transported to the retail market or to a cold room; **Step 05:** crops are re-sorted and stored in the cold room to extend their shelf life; **Step 06:** crops are purchased by consumers.



## 2.2 FACTORS INFLUENCING CROP QUALITY AT THE POST-HARVEST LEVEL

To prevent post-harvest quality losses, it is essential to maintain well-controlled conditions. The main parameters influencing product quality are **temperature, relative humidity, and gas concentrations in the environment.**

i) **Temperature** is the most crucial factor in preserving crop quality. Therefore, the availability of pre-coolers (including room, hydro, vacuum, ice, and forced-air cooling) and a well-controlled refrigerated environment is essential for an effective post-harvest chain.

In cases where pre-coolers are not available at the farm or packhouse, several conventional methods can help reduce the temperature of fresh produce after harvest. These methods include natural ventilation (storing in a shelter at the farm), utilising passive evaporative coolers, or scheduling harvests for the early morning hours.

Moreover, mobile refrigeration equipment, such as refrigerated containers or trailers, can be employed to cool down the product consistently. It is important to note that while cooling in a cold storage room can be an

alternative when pre-cooling is not possible, extremely low temperatures should be avoided to prevent chilling or freezing injuries.

ii) When it comes to **relative humidity (RH)**, there's a trade-off. If RH is too low, it can lead to product dehydration and shriveling. On the other hand, high RH increases the risk of condensation, which can accelerate mold growth on the product's surface.

iii) **Ethylene** is a plant hormone that induces ripening. To prevent premature ripening, it's crucial to keep ethylene concentrations as low as possible, except in designated ripening or degreening rooms. This can be achieved using ethylene scrubbers or by exposing products to an ethylene blocker, such as 1-Methylcyclopropene (1-MCP), as shown in **Figure 2.2.**

iv) Modifying the **air composition** (oxygen and carbon dioxide) using techniques like modified atmosphere packaging or controlled atmosphere storage rooms significantly affects product quality (refer to **section 2.7** for details). Additionally, it's important to prevent mechanical damage by handling products with care and using suitable packaging (see **section 2.10** for details).

a)



b)

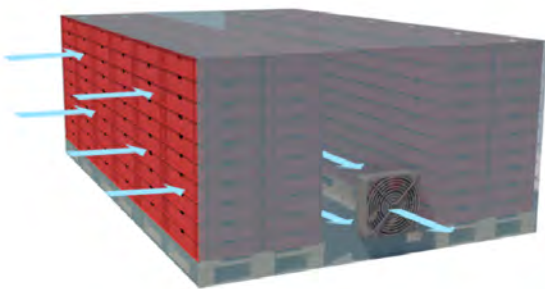


## 2.3 HOW FAST DO FRUITS AND VEGETABLES COOL?

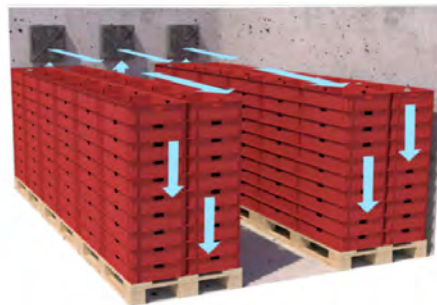
After harvest, the field heat should be removed as fast as possible since fruits and vegetables stay fresh much longer at lower temperatures. Typically, if the produce is cooled by 10 °C below the ambient temperature, its storage life doubles, and sometimes, triples. **The speed at which produce cools down depends on the air speed, set air temperature, size of the products, packaging type, and the quantity of products being cooled.** Larger fruits and vegetables cool down slower than smaller fruits and vegetables.

In precoolers (**Figure 2.3**), high-speed (0.1-1 m/s) horizontal airflow can cool down the product in one day (**Figure 2.4**). In refrigerated containers, vertical, low-speed airflow in the packages (0.01-0.06 m/s) cools down the product in a matter of days (**Figure 2.4**). In refrigerated cold storage rooms, it can take over a day to bring down the crops' temperature. **In order for cold air to access the fresh produce, ventilated packaging is essential. These can be cardboard boxes or plastic crates with vent holes.**

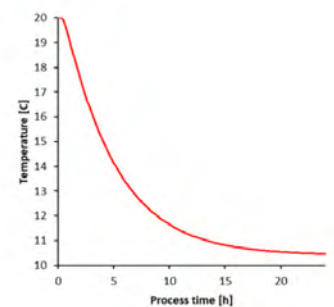
a) Airflow in a pre-cooling facility



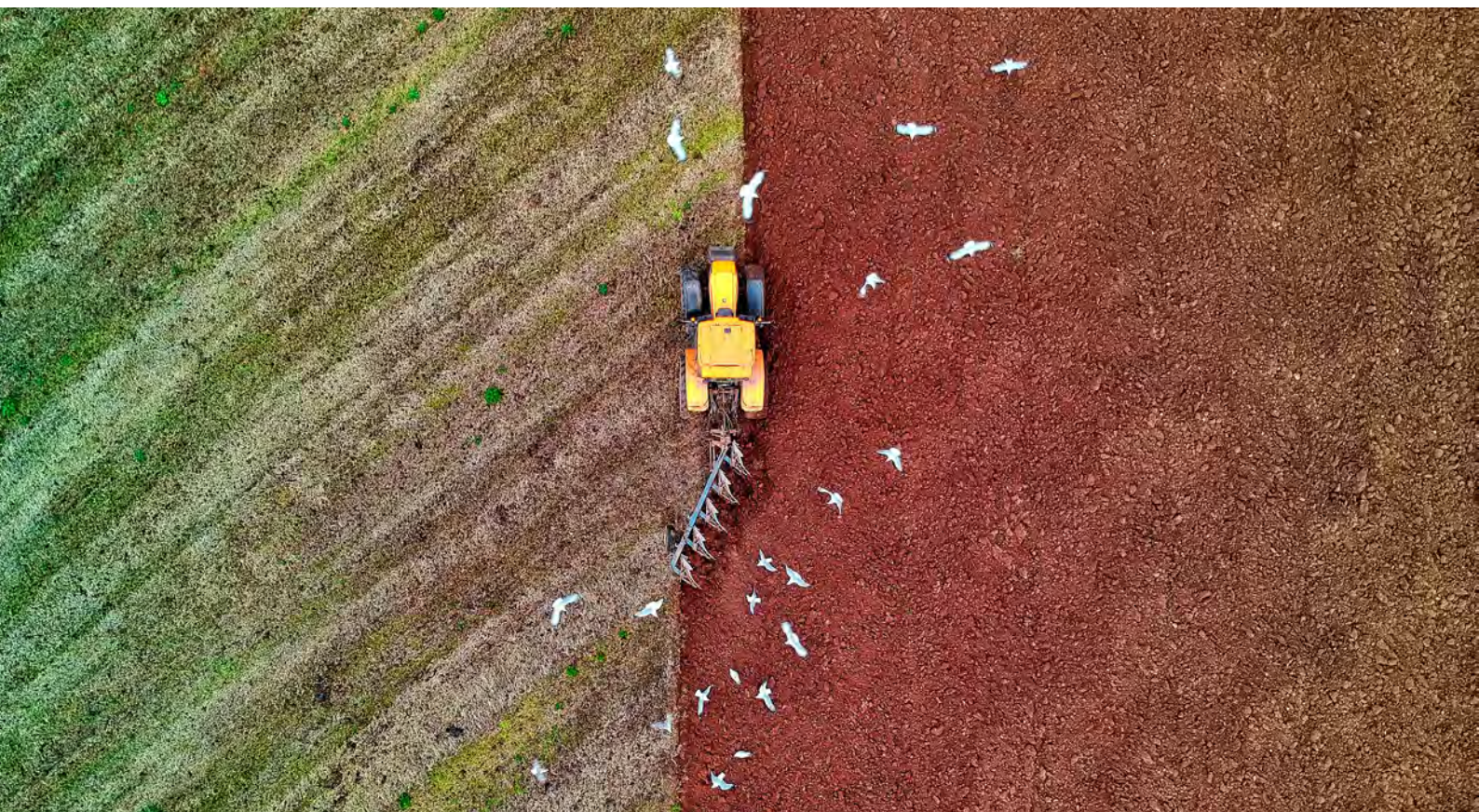
b) Airflow in a cold storage room



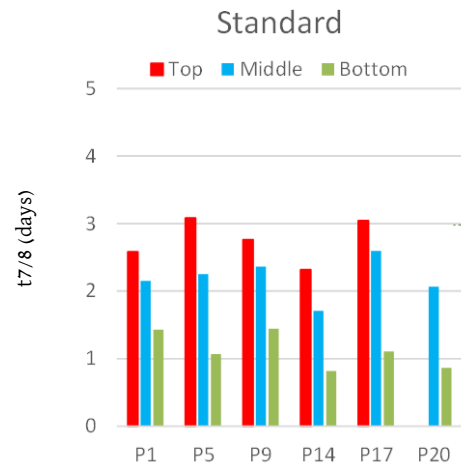
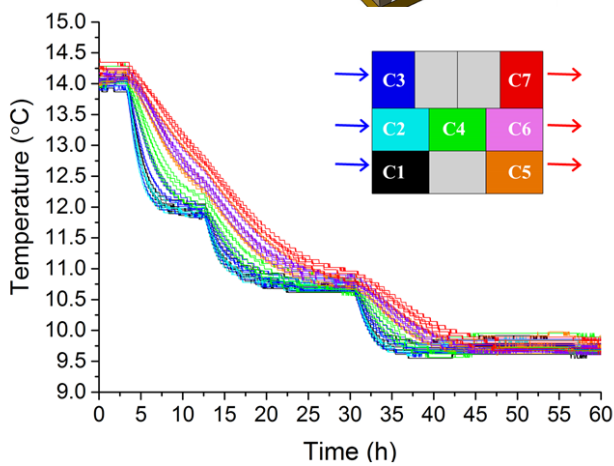
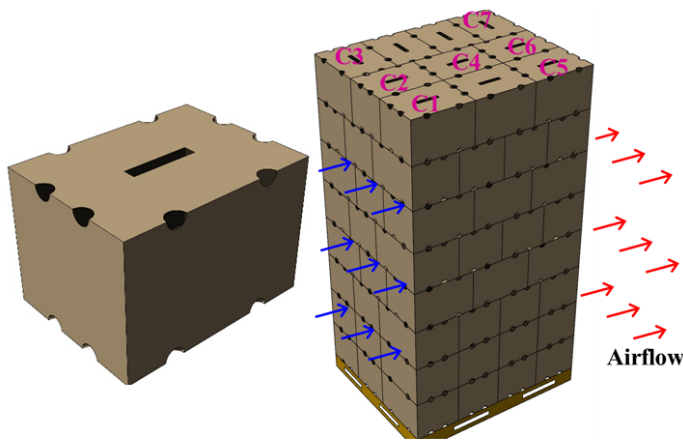
c) Cooling of a single fruit: fruit pulp temperature over time



*Source: We acknowledge the support of Dario Bundi in making the figure (a-b)*



**Figure 2.4:** (a) Pre-cooling temperature profiles for a pallet of citrus fruit, packed in ventilated cardboard packaging. Step down cooling is applied in different stages. (b) Cooling time for different pallets (P1-P20) of citrus fruit, packed in ventilated cardboard packaging in a refrigerated container.



## 2.4 WHERE SHOULD YOU PLACE SENSORS IN THE COLD ROOM?

Temperature and humidity sensors are often placed in a cold storage room to monitor the interior conditions. The placement of the sensor in the room is dependent on its purpose.

- i) If you want to verify the cooling air temperature, the sensor should be placed near the inlet of the cold air.
- ii) If you want to monitor the worst location in the cold room, i.e., where the fruits and vegetables are the warmest or cool down the slowest, the answer is more complicated. Often these worst locations are the boxes far away from the cold air inlet. The reason is that the air needs to travel a long distance to reach these boxes and can absorb heat from the other fruits and vegetables along the way. Note that fruits and vegetables deep inside a box or pallet will cool the slowest.

**AS A RULE OF THUMB, THE WORST LOCATION WILL LIKELY BE FAR AWAY FROM THE INLET AND DEEP INSIDE THE BOXES OR PALLETS.**

However, every cold store has its own airflow distribution, making recommendations regarding the placement of sensors difficult to generalise. Furthermore, some parts of the products can already be cool, as they were placed earlier in the room.



## 2.5 WHAT ARE THE BEST PRACTICES TO MANAGE MULTI-COMMODITY COLD ROOMS?

Different fruits and vegetables with different optimal temperatures often have to be stored simultaneously in a cold room or when transported, in a refrigerated truck. On these occasions, it is crucial to properly manage multi-commodity rooms or refrigerated transport to reduce the increased spoilage of one crop over another, as all crops have varying optimum storage temperatures.

Mainly two types of crops can be identified based on storage temperature:

i) First, the crops with an optimal temperature of around 0 °C should ideally be stored at low temperatures since a slight increase in temperature drastically decreases the storage life.

ii) Secondly, some crops require a higher temperature. These crops are generally characterised by a short storage life. Consequently, we could divide the commodities into two groups: **Group 1: optimal temperature < 7 °C** (storage group 'cold' in Table 2.1) and **Group 2: optimal temperature > 7 °C** (storage group 'warm' in Table 2.1). Transport organisations or retailers use two or more other groups as well.



























When two storage rooms are available, one room could operate below 7 °C while the other could be set to a higher temperature (> 7 °C). When only one room is available, the temperature in the room has to be adapted to minimise the quality loss of all crops. **In general, the temperature should be increased to the highest optimal temperature of all the crops in the room to prevent chilling injury, despite the loss in the storability of the commodities of group 1.**

However, the temperature in the room will not be uniform. These temperature gradients could be used to optimise multi-commodity rooms, as chilling injury-sensitive products can be put at these warmer spots without increasing the temperature in the rest of the room. Besides, the cold room design could be manually changed to generate warmer zones, for example, by hanging tarpaulins to create different compartments within the room.

Another essential consideration in multi-commodity rooms is ethylene. **Ethylene triggers the ripening of various crops.** When storing multiple crops in one room, attention must be paid to not placing an ethylene-producing crop with a highly ethylene-sensitive crop, as the storability of the latter might be reduced. Since the air within the room recirculates, there is no outlet for the ethylene produced to leave the room. As much as possible, ethylene-producing and ethylene-sensitive crops should be stored in separate units. If that is not an option, they should be kept far apart, and ethylene scrubbers should preferably be installed. **Table 2.1** indicates which crop is considered a high ethylene-producing or sensitive product.

Note that storing the wrong products together can result in a significant loss of product quality and market value, especially during a long storage period. Outturn results can vary due to variability in initial quality, handling process during harvest, loading patterns, transport logistics to the cold rooms, and other factors. Therefore, experience and prior knowledge of all risks are essential in managing multi-commodity rooms.

TABLE 2.1: List of commodities with the optimal storage temperature and ethylene-sensitivity <sup>22, 23</sup>

Commodity	Optimal storage temperature (C°)	Ethylene production	Ethylene sensitivity	Storage group based on temperature	Storage group based on ethylene*
Apple 	-1 to 0	very high	high	cold	P
Banana 	13 to 15	moderate	high	warm	P
Bell Pepper 	7 to 10	low	high	warm	N
Bitter Gourd 	10 to 12	low	moderate	warm	S
Cabbage 	0	very low	high	cold	S
Carrot 	0	very low	high	cold	S
Cassava 	0 to 5	very low	low	cold	N
Cauliflower 	0	very low	high	cold	S
Coriander 	0 to 1	very low	high	cold	S
Cucumber 	10 to 12	low	high	warm	S
Eggplant 	10 to 12	low	moderate	warm	S
Grapes 	-0.5 to 0	very low	low	cold	N
Guava 	5 to 10	moderate	low	warm	P
Lady Finger 	7 to 10	low	moderate	warm	S
Mango 	13	moderate	moderate	warm	P
Melon 	5 to 10	moderate	high	warm	P
Orange 	3 to 9	very low	moderate	cold	S
Peach 	-0.5 to 0	moderate	moderate	cold	P
Pear 	-1.5 to -0.5	high	high	cold	P
Peas 	0	very low	moderate	cold	S
Plantain 	13 to 15	low	high	warm	S
Potato 	4 to 8	very low	moderate	cold	S
Raspberry 	0	moderate	moderate	cold	P
Strawberry 	0	low	low	cold	N
Tomato 	8 to 13	low	moderate	warm	S
Green Beans 	4 to 7	low	moderate	cold	S

How to read the table: Crops can be placed together based on ethylene-sensitivity, you can refer to the colors in columns 3 (Ethylene Production) and Column 4 (Ethylene Sensitivity).

●● = X   ●●● = X   ●●●● = X   ●●●●● = ✓   ●●●●●● = ✓   ●●●●●●● = ✓   ●●●●●●●● = ✓   ●●●●●●●●● = ✓   ●●●●●●●●●● = ✓

\*P: ethylene-producing: these crops are considered as ethylene producing crops; S: ethylene-sensitive: these crops do not produce significant amounts of ethylene and are considered to be very sensitive for ethylene, N: neutral: these crops do not produce significant amounts of ethylene and are not considered sensitive to ethylene.

## 2.6 HOW IS THE POST-HARVEST LIFETIME OF CROPS DETERMINED?

The optimal storage temperature varies significantly among different crop types, cultivars, and even within the same cultivar. **Factors that influence the optimal storage temperature include the maturity stage at harvest, crop cultivar, pre-harvest growing conditions (such as environmental temperature and precipitation), and post-harvest handling.** Furthermore, due to the nature of biological products, each fruit will react differently due to biological variability. This variability further complicates the determination of a general optimal storage temperature.

To analyse the effect of storage temperature on storability, **Figure 2.5** displays the storage life (in days) as a function of temperature. These results were computed by creating digital food twins for various crops. These digital twins simulate the aging of physical crops and forecast the ideal time window for selling products before they spoil, using real-time data from hygrothermal sensors installed within the cold rooms (see **Chapter 5.3**).

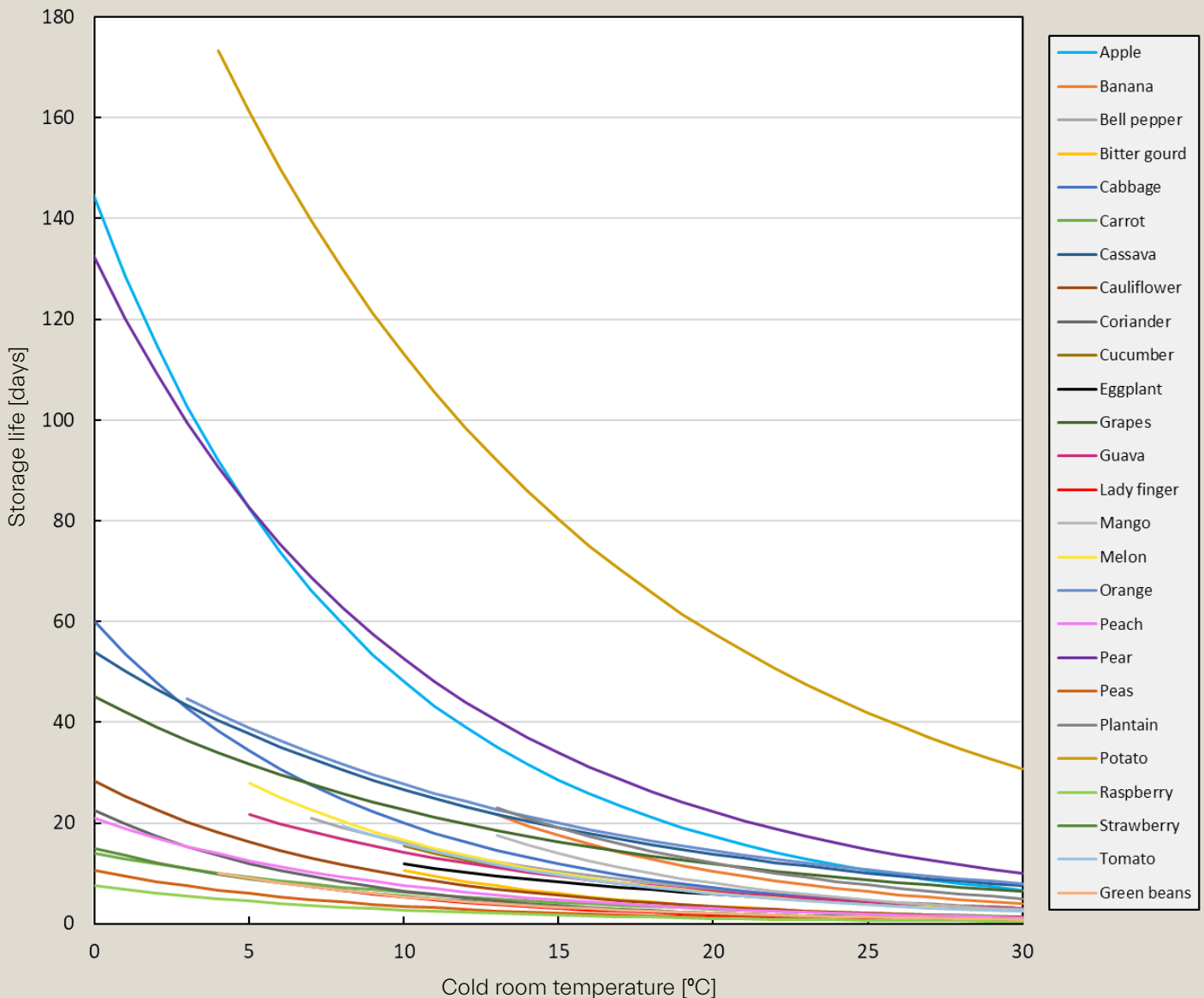


The digital twin model assumes that the crops are stored immediately after harvest at a commercial ripening stage in the case of climacteric produce\* (with an initial quality of 100 percent), while the product is considered spoiled when its quality drops below 20 percent.

The results show how the optimal temperature and storability vary significantly between the crops. The storability of each crop decreases considerably as the storage temperature increases, especially at low optimal temperatures. The graph illustrates the increase in storage life days per °C reduction in storage temperature. Based on these calculations, **Table 2.1** presents an easy-to-use visual to determine the optimal storage temperature range for the crops with a digital twin in Your Virtual Cold Chain Assistant's Coldtivate app (see **Chapter 3.2**).

\*Produce is sorted into two groups: climacteric and non-climacteric, based on maturation, ethylene, and ripening. Climacteric items, like bananas and tomatoes, keep ripening after harvest, releasing more ethylene initially that decreases after peak ripeness. On the other hand, non-climacteric produce, like citrus fruits and berries, stops ripening after harvest and matures only while attached to the plant.





**Figure 2.5:** Expected storage life is a function of storage temperature. The minimum temperature of each curve corresponds with the temperature where chilling injury is expected to occur.<sup>24, 25</sup>

**The information in Figure 2.5 can be interpreted as follows:**

Apples (light blue curve) and pears (purple curve) stored at 0 °C have a storage life of approximately 4 months. However, if they are placed in a cooler room with a temperature of 10 °C, their storability decreases to roughly 50 days.

Melons (bright yellow curve) cannot be stored at very low temperatures (the curve starts at 5 °C). Even at the optimal temperature of 5 °C, their storage life is relatively short, around 30 days. If the temperature is increased to 15 °C, the storage life drops to only 10 days.

Therefore, when dealing with multiple crops, it is important to consider the effect of room temperature on the storability of each crop. This assessment should take into account the expected or required storage life for each specific crop.

## 2.7 HOW DO THE GASES IN THE ROOM AFFECT THE STORAGE LIFE OF THE PRODUCE?

In addition to the temperature, the respiration rate of fresh produce is also impacted by the gas composition inside the room. Hence, to further prolong the storage life of the products, controlled atmosphere (CA) storage can be implemented in addition to refrigerated storage. The O<sub>2</sub> concentration is reduced during CA storage while the CO<sub>2</sub> concentration is slightly increased. In this way, the physiological processes in the fruit or vegetables are slowed down. **Table 2.2** lists a few commodities where implementing CA storage is beneficial.

When CA storage is implemented, entrance into the room is restricted due to the low O<sub>2</sub> concentrations. Consequently, CA storage is only advantageous when a storage room is intended for long-term storage, e.g. a room fully filled with apples, so the doors can be opened sparingly. The cool room should have an O<sub>2</sub> and CO<sub>2</sub> sensor and a CO<sub>2</sub> scrubber to implement CA storage. When the room is airtight, the O<sub>2</sub> concentration automatically drops due to the respiring products within the room. Too low O<sub>2</sub> conditions can be prevented by adding atmospheric air into the room. Excess CO<sub>2</sub> produced by the crops is removed by the scrubber.

TABLE 2.2

CROP	O <sub>2</sub> (%)	CO <sub>2</sub> (%)	Expected increase in storage life
Apple	2	< 1	± 3 months
Pears	3	< 0.7	± 3 months
Raspberry	10	8	± 10 days (storage up to 2 weeks)
Strawberry	3	10	± 10 days (storage up to 2 weeks)

Table 2.2: Examples of crops where CA storage would be beneficial, together with the optimal O<sub>2</sub> and CO<sub>2</sub> concentrations and the expected storage life extension



## 2.8 WHAT IS SORTING, AND WHY IS IT IMPORTANT?

**Sorting in the fresh produce supply chain involves separating unsuitable fresh produce and foreign materials from a lot of marketable fresh produce.**

Freshly harvested produce may become unsuitable for the market or cold storage if it sustains mechanical injuries, becomes infested with insects, succumbs to diseases, is harvested either prematurely or when overripe, or becomes distorted, among other factors. Additionally, the quality of fresh produce at harvest and throughout the post-harvest supply chain can be influenced by biological variability resulting from variations in pre-harvest cultural practices. Notably, for climacteric fruits, such as tomatoes, mangoes, bananas, apples, and avocados, the stage of maturity at harvest significantly impacts their quality during the post-harvest supply chain. Therefore, sorting plays a crucial role in reducing these variations, focusing primarily on external quality attributes.

Following the harvest of fresh produce, including fruits and vegetables, various field operations, such as sorting and grading, are often conducted before packing, particularly for produce that is highly sensitive to repeated handling. As illustrated in **Figure 2.1**, sorting can occur at different stages, including on the farm (**Step 1**), at the packhouse (**Step 3**), and upon arrival at retail markets (**Step 5**).

Sorting at the farm, primarily based on visual inspection, serves several purposes. It helps eliminate foreign materials like plant debris, soil, and stones from the produce and reduces the volume of produce that needs to be transported from the farm to the packhouse, which is especially important for the export cold chain. Any unnecessary material should be disposed of properly away from the packing area.

On the other hand, sorting at the packhouse is focused on improving the quality and uniformity of the lot, rather than individual items. This can be accomplished either manually, relying on human vision, or automatically, using computer vision and hyper-spectral imaging techniques based on factors like color, shape, and size.

In commercial-scale manual sorting at the packhouse, conveyors are often utilised, with their suitability depending on the type of fresh produce and the specifics of the supply chain. Fruit-sorting inspectors in manual sorting operations must undergo sufficient training to effectively identify culls based on criteria such as color, size, shape, and blemishes.

Advanced automatic electronic sorting systems, on the other hand, employ cameras (e.g., computer vision, hyper-spectral, etc.) to sort fruits based on attributes like color, size, shape, and blemishes. These cameras can detect culls and remove them from the lots as they pass through a conveyor. Such operations are made possible through the use of image analysis or specialised computer software.

Electronic color vision sorting, categorised by color, has become the standard for many crops, including apples, citrus, and tomatoes. This is because the initial capital cost of implementing a sophisticated automated sorting system can be high. For instance, oranges, tangerines, and lemons can be sorted into various color categories. Lemons, for instance, can be categorised into four color classes: dark green, light green, silver, and yellow, all accomplished through electronic color sorters. Additionally, commercial sorting machines can be used to weigh fruit and employ integrated cameras with multiple views to estimate volume, thereby calculating density.



## 2.9 WHAT DOES GRADING MEAN, AND WHY IS IT IMPORTANT?

**Grading is a post-harvest handling activity that entails separating and categorising fresh produce according to criteria such as size, weight, maturity, and color.**

The grading of fresh produce in the post-harvest supply chain typically occurs at the packhouse (as shown in **Figure 2.1, Step 3**). This process involves manual inspection by experienced graders who assess the produce based on criteria like size, blemishes, color, weight, and defects. At the packhouse, fresh produce is placed on a moving belt conveyor, and workers visually identify and remove any defective items from the moving lot.

The off-grade produce that is separated from the lot is then packed and sent for processing or juice extraction. The inspection for this quality control process is more precise compared to sorting. Graders need to be trained to recognize specific attributes, such as the percentage of blemished areas on the fruit's surface, to ensure that no off-grade fruit is included in the lot. Grading is performed according to the requirements of a grading standard, which may vary by country and specifies the grade classification.

Automated grading is also commonly employed, particularly in more advanced cold supply chains. High-speed electronic graders and photo-optical grading systems are used to assess fruits and vegetables based on factors like blemishes and color. Additionally, internal quality attributes such as sugar level and juice content can be determined using near-infrared spectroscopy. This information, both internal and external quality, is combined and processed by computer software to accurately determine the grade and marketability of the fruit.

## 2.10 WHAT ARE THE BEST METHODS TO PACKAGE THE CROPS, IN PARTICULAR WITH REGARD TO HYGIENE AND LIFETIME?

Packaging is often carried out at the packhouse (**Figure 2.1, Step 3**). The products should be handled carefully, and the packaging applied according to best practices.

i) The packaging should facilitate proper airflow within the container to dissipate the heat produced by the produce's respiration. An ideal ventilated package should be designed with a sufficient number and size of vent holes to enable rapid and uniform cooling of the items stored inside. Moreover, the effectiveness of the packaging is significantly influenced by the individuals responsible for manually packing the fruit.

In general, there are two primary types of packaging: plastic containers and cardboard boxes. Cardboard boxes are easy to manufacture and, as a result, are the most commonly used. However, they have relatively low mechanical stability, which limits the size and number of vent holes that can be incorporated into the packaging. Additionally, in high humidity environments, cardboard boxes may become unstable and prone to collapse due to moisture absorption, potentially leading to damage to the products inside. On the other hand, **plastic containers are recommended** because they offer mechanical stability even when designed with numerous perforations and when exposed to high humidity conditions. Furthermore, they can be sanitised before use to prevent mould growth.

ii) Crops that are highly sensitive to dehydration and prone to shrivelling, such as leafy vegetables like lettuce, are best packaged in plastic bags. Similarly, products that produce high levels of ethylene, like bananas, should be covered with plastic to prevent the spread of ethylene within the storage room.

However, when products are wrapped in plastic, it restricts airflow around them. This can result in less efficient removal of respiratory heat, causing the package to have a slightly higher temperature. If non-perforated plastic is used for wrapping and the temperature becomes high, there's an increased risk of developing low oxygen conditions within the package. For instance, when the package is removed from the storage room, the oxygen concentration will rapidly decrease due to the increased respiration rate of the product. This low oxygen environment can lead to product fermentation, resulting in significant quality losses.

To address this issue, it's possible to carefully adjust the gas permeability properties of the plastic to achieve appropriate gas concentrations within the package. This practice is known as modified atmosphere packaging.

iii) When fruits and vegetables incur bruises, it prompts them to release more ethylene, subsequently accelerating the ripening of nearby produce. Movement and mechanical vibration during transportation can lead to damage in the fruit. If the skin is damaged, it allows the nutrient-rich fruit or vegetable flesh to be exposed to the environment, resulting in the growth of molds and microbiological decay.

Hence, it's essential to handle soft products, such as berries, grapes, or peaches, with care during packaging and transportation. While plastic containers offer better ventilation for crops compared to cardboard boxes, they are more likely to cause mechanical damage. In such instances, the use of protective foams or poly liners could help safeguard the products.



## Chapter 03

# RUNNING COLD ROOMS USING SERVICISATION AND DIGITALISATION

In January 2021, BASE and Empa launched the Your Virtual Cold Chain Assistant (Your VCCA) project, which consists of a two-part solution aimed at reducing post-harvest food loss, improving farmer livelihoods, and enhancing food security. Firstly, Your VCCA includes a pay-per-use or servitisation business model that makes cooling more affordable and accessible for smallholder farmers and small-scale traders. As a second layer, it equips them with post-harvest intelligence through a data-science-based mobile application called Coldtivate. This empowers farmers and traders to secure the best possible price for their produce and break free from the vicious cycle of poverty.

YOUR VIRTUAL COLD  
CHAIN ASSISTANT

## 3.1 WHAT IS COOLING-AS-A-SERVICE?

### 3.1.1 The Problem: Market barriers

Some barriers prevent farmers from accessing the sustainable cooling solutions needed to save food. These barriers include high upfront investment costs for equipment, limited access to finance, uncertainty related to new technologies, limited technical knowledge of cooling systems and hygrothermal sensor data, a lack of expertise in post-harvest storage practices, and, in some cases, unreliable access to electricity.

### 3.1.2 The Solution: Business model innovation

Innovative business models such as Cooling-as-a-Service (CaaS), allow smallholder farmers to access cold storage by paying a small fee per crate per day. This model enhances food quality, increases food value, and reduces waste. **CaaS operates on a servitisation strategy, wherein beneficiaries purchase cooling services instead of having to invest in and manage the infrastructure themselves.** This approach eliminates the need for farmers to bear capital expenses associated with asset ownership, a hurdle often considered the most significant barrier to accessing cold storage.

Service providers own and maintain the cooling facilities, effectively shouldering the operational costs. By also bearing the performance risk of the cold room, service providers are incentivized to install the most energy-efficient equipment and provide high-quality maintenance to prevent downtime.

In the context of providing farmers with access to cold storage, this model typically does not require users to sign long-term contracts, unlike larger cooling projects in sectors such as real estate, commercial, or industrial. In practice, this means that farmers can visit the multi-commodity cold rooms at any time during opening hours. They can hand over a certain amount of produce to the cold room operator, who appropriately stores it in the cold room. Farmers can then retrieve their produce when they need to sell or transport it. Payment is made directly to the operators, either in cash or digitally, upon withdrawal of the crop. The amount charged is calculated based on the quantity of food stored (in terms of crates or kilograms) and the duration of storage in days.





### 3.1.3 Key stakeholders involved

Various stakeholder groups can benefit from CaaS, including:

i) **Cooling beneficiaries:** This category encompasses smallholder farmers and small-scale traders.

Smallholder farmers, as the name suggests, cultivate small volumes of crops on relatively small plots of land, typically less than two hectares. They may or may not own the land they farm on. These farmers generally have fewer resources compared to commercial-scale farmers and often operate within the informal economy. They are frequently among the most vulnerable participants in the agricultural supply chain.

Small-scale traders engage in the buying and selling of agricultural produce on a limited scale, often at local markets or roadside stands. Without access to suitable storage facilities, they face challenges related to the limited shelf life of their produce. This constraint diminishes their ability to negotiate favorable prices, resulting in rushed sales and struggles to obtain equitable prices for their merchandise.

ii) **Farmer groups or Farmer Producer Organisations (FPOs):** Clusters of farmers can be organised into Farmer Producer Organisations (FPOs). These organisations are composed of farmer-producers and offer comprehensive support to small-scale farmers, encompassing various aspects of cultivation, including the provision of inputs, technical assistance, processing, and marketing services.

The formation of Farmer Producer Organisations (FPOs) by aggregating marginal, small, and landless farmers has proven to be instrumental in enhancing market linkages and improving the economic well-being of farmers.

These organisations provide a wide range of services, covering technical assistance, processing, marketing, and the supply of cultivation inputs, thereby offering comprehensive support to farmers. Within the context of CaaS, FPOs can assume different roles. They can act as customers of the cooling service, work as cooling operators to make the service accessible to their members, or even purchase fresh produce from their members. By leveraging cold storage facilities, they can secure better prices for their produce, effectively providing valuable market linkage services.

iii) **Cold room manufacturers:** These companies produce decentralised, solar-powered cold rooms designed to deploy cutting-edge cooling technologies for the benefit of smallholder farmers and traders. These cold rooms are characterised by their use of environmentally friendly refrigerants, reliance on thermal energy storage rather than chemical energy storage (batteries), modular construction, and the provision of multiple chambers.

iv) **Cooling service providers:** These companies offer cold room services to individual farmers or FPOs in exchange for service charges. These companies may either manufacture cold rooms in-house or procure them from third-party manufacturers. Within the Your VCCA project, we exclusively work with cold rooms powered by clean energy sources such as solar or biomass, although these cold rooms can also be connected to the grid for additional power requirements. These cooling companies not only provide cooling facilities but also facilitate market access for farmers by connecting them with potential buyers, thereby reducing information gaps. For example, self-help groups overseeing cold rooms monitored by Koel Fresh, a cooling company in India, conduct market research to identify potential hotels, hostels, and retailers where farmers using the cold rooms can collectively sell their produce (Read the full case study [here](#)).

## 3.2 DIGITAL INNOVATION

### 3.2.1 What are the features of Coldtivate?

**Coldtivate is designed to support cold room operators to efficiently operate cold rooms and to provide cold room users with insights on how to best make use of post-harvest cooling to decrease food loss and increase their incomes.**

The app serves as a digital inventory management system, streamlining the recording of produce check-ins and check-outs in cold rooms. This allows operators and registered company employees to remotely monitor room occupancy and revenue, eliminating the need for manual registers and accounting. At the same time, cooling users get an overview of what they have stored across rooms and can adjust their harvesting behaviour to the current occupancy level of the rooms to minimise outdoor, unrefrigerated storage time.

The app employs physics-based models that take into account factors such as the commodity type, initial produce quality upon arrival at the cold room, and the room's temperature profile, which is collected through hygrothermal sensors within the room. These models **calculate the optimal crate pickup times** based on the remaining storage life\* of the commodity and provide precise predictions about the remaining quality of each crate. Additionally, the app integrates a machine-learning model that **forecasts market prices** specific to each commodity at various locations. These combined features offer valuable guidance to cooling users, enabling them to determine the ideal timing and locations for selling their produce to secure higher prices and minimise food spoilage.

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\*Coldtivate utilises a storage life model instead of a basic shelf life model. In essence, the app recommends that cooling users check out their produce when there is still a 0.5-day shelf life remaining, allowing them some time for transportation and marketing without the risk of crop spoilage. **More information on the storage life model is available in Chapter 5, section 5.3.**

Coldtivate also includes a **Knowledge Hub**, which serves as a repository of best practices for post-harvest handling. This includes information on ideal storage temperatures for specific crops and advice on maintaining cold storage rooms. The Knowledge Hub is designed to assist operators and farmers in comprehending how to efficiently employ cold storage technology within a streamlined food supply chain.

### 3.2.2 How can each of the three stakeholders – farmers, cold room operators, and cooling companies – use Coldtivate?

i) Local entrepreneurs providing cold storage services are encouraged to leverage Coldtivate for streamlining their operations. By integrating cooling units and operators into the app, they can enhance room management efficiency and remotely monitor key parameters like temperature, occupancy, and revenue generated by each room.

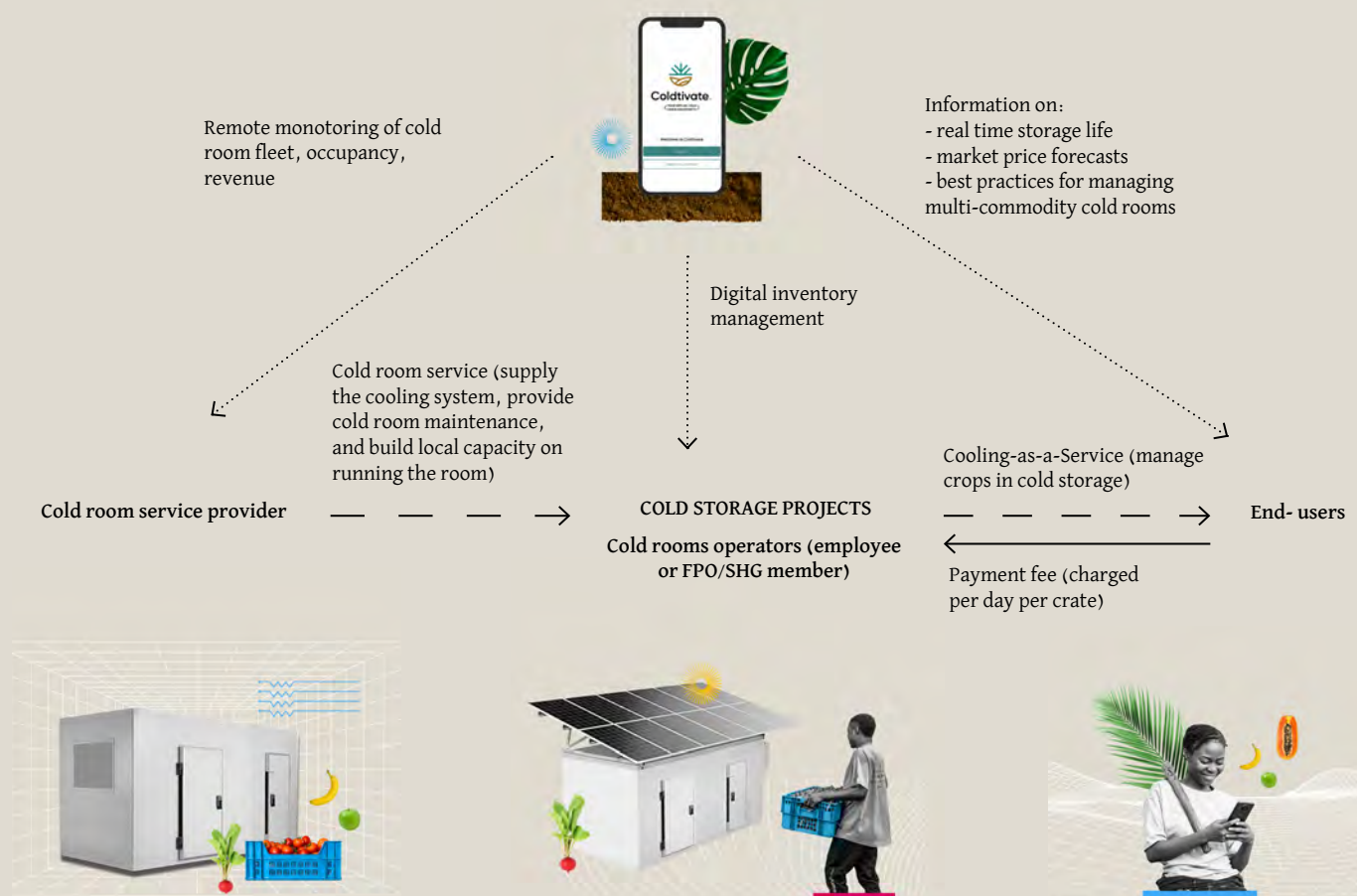
ii) Coldtivate empowers cold room operators to digitally oversee room inventory and automate reporting procedures. Additionally, it offers guidance on optimising room operations to reduce spoilage and enhance customer satisfaction.

iii) Farmers, traders, and other potential cold room users can utilise Coldtivate to acquaint themselves with cold storage technologies. They can also access information about the locations of cold rooms and estimate the potential advantages of using cold storage. While utilising the rooms, farmers can remotely track temperature and occupancy in the room where their crates are stored. Furthermore, they receive notifications about remaining storage life and market prices, enabling more informed decisions regarding the optimal time to sell their produce.





Figure 3.1: Interaction between the key stakeholders under CaaS, and how Coldtivate benefits each one of them.



### 3.3 DIVIDING OPERATIONAL ROLES AND RESPONSABILITIES UNDER CAAS

The operation of cold rooms in the agricultural sector under the CaaS model involves coordination among three primary entities: the cooling company, the room operator, and the end-users, which may include farmers and small-scale traders. This relationship is illustrated in **Figure 3.1**. While the specific roles and responsibilities between the cooling company and operators can vary based on factors like the technology provider's local presence, the skills of youth and women involved, and their specific technical requirements, the following section outlines two common structures observed within the Your VCCA project:

**i) When the cooling company retains ownership of the cold room:** In one of the observed models within the Your VCCA project, a private company acts as the cooling service provider. In this arrangement, the company makes the initial investment in the cold storage infrastructure, taking ownership, operational responsibility, and maintenance tasks. In return, it collects metered payments from users of the cold storage facilities. The company also assumes responsibility for covering various fixed costs, including utilities, rent, leases, and other associated expenses.

To finance the cold storage infrastructure, the cooling company often raises funds and may receive support from both private and government entities. They may choose to contract the cold room infrastructure from a manufacturer and incorporate additional solar panels and complementary power supply systems to operate the refrigeration system. Alternatively, some service providers manufacture and supply the cold room infrastructure themselves.

Under the servitisation model, users are not required to cover any initial setup costs for the cold rooms. In this scenario, the service provider has several options. They may choose to raise the necessary capital to retain ownership of the cold rooms within their balance sheet. They can also transfer ownership of the cold rooms to one or more investors, often facilitated through the establishment of a special-purpose vehicle. Within this framework, the cooling company retains flexibility in selecting operators for the cold rooms. They can either directly appoint their own operators or opt to hire individuals from the local community. These operators undergo training to perform various tasks, including adjusting the temperature settings of the multi-commodity cold room according to the stored horticultural crops, overseeing inventory management, and handling billing procedures.

Involving operators from the same village or town where the cold room is located creates a mutually beneficial arrangement for both the cooling company and the local community. Since the local operators are well-connected with their community, their presence and understanding of cooling systems can help build trust in the solution among their peers and community members. Additionally, they can engage with various stakeholders to assess whether the cooling services are indeed contributing to increased incomes for farmers and gather candid feedback. In exchange for their services, cooling companies provide skill development opportunities and alternative income-generating activities to households engaged in farming. This collaborative approach strengthens the bond between the cooling company and the local community, fostering a sense of shared progress and sustainable development.

**The operator serves as the primary point of contact for the cold room.** They engage with farmers and traders on a daily basis, establishing routines for crop drop-offs and pickups. They also bear the responsibility of securing and unlocking the cold room doors. To ensure effective operations, it is recommended to assign a **project manager** from the cooling company (referred to as a 'registered employee' on Coldtivate) to each site. These project managers provide close support to the local operators, addressing any queries or concerns.

Operators should undergo training to assist farmers in sorting their crops, separating bruised or mechanically damaged pieces from undamaged produce. Farmers are encouraged to sell slightly bruised produce at a reduced price instead of discarding it, thereby minimising food waste. Crops that have exceeded their shelf life and show signs of decay can be composted. The cooling companies should provide a compost pit or facility at the cold rooms, or arrangements can be made at local markets by the local government.

After sorting, operators record the initial quality of the produce, estimated by the number of days since harvest. This data is entered into Coldtivate before they proceed to weigh, load, and unload the produce in crates.

The operator collects fixed storage fees in cash from farmers daily and places the payments in a lockbox. Weekly, they deliver the total sum to the project manager. Since operators are present at the room daily, they should be trained to spot system issues, like cooling failures or wire damage, and report them to the project manager (elaborated upon in **Chapter 4**). The project manager then arranges inspections and necessary repairs with the technical team or manufacturer.

The **project manager**, a full-time employee of the cooling company, operates behind the scenes, supporting and overseeing the operator's work. In Coldtivate, both the project manager and other cooling company employees should register as '**registered employees**'. With their deep understanding of the local agricultural supply chain and markets, the project manager conducts a needs assessment focused on cold storage services in horticultural-producing regions and villages. By analysing factors such as farmers' travel distances to markets, crop types, and reasons for low returns, the project manager determines whether there is interest in establishing a decentralised cold room. If interest exists, they initiate the process of identifying and mobilising farmers, who can then store fresh produce for the duration recommended by Coldtivate.

To maximise cooling benefits for farmers growing various crops, the project manager should create a seasonal calendar, which helps precisely determine ideal temperature ranges for common fruit and vegetable combinations. They are also advised to leverage Coldtivate's forecasts of room occupancy in the coming days to devise a monthly farmer schedule. This approach ensures that refrigeration space usage aligns with customer needs, matching daily crop volumes with the cold room's capacity.





## ii) When a community-based group retains or gets transferred the ownership of the cold room

Community-based groups, such as FPOs in rural areas and self-help groups (SHGs) in urban areas, can acquire ownership of cold rooms through two means:

- **Self-Financed Setup:** They can establish the infrastructure using their own funds and financial assistance from government schemes. In this case, the cooling service provider's role is typically limited to supplying equipment, providing technical maintenance, and building capacity for cold room use.
- **Collaborative Ownership:** Alternatively, they can take over or help run rooms established by entrepreneurs. Members from these groups then take on operational and project management responsibilities.

For FPOs or SHGs, the end-users are typically their members and other smallholder farmers. They can offer three different models:

a) **Pay-Per-Use Model:** End-users access cooling on a pay-per-use basis and manage crop sales independently.

b) **Market Linkage Model:** The FPO or SHG offers market linkage services, purchasing crops from users at fair prices, storing them for better market conditions, and potentially transporting them to higher-paying markets. Profits cover cold room operation, salaries, and logistics, with any surplus benefiting members or investing in farmer inputs.

c) **Custody Model:** In this model, users entrust their produce to the FPO or SHG, which leverages the cold rooms to await better prices. Profits generated from the sale of the stored produce can be managed in several ways within this model. One approach involves sharing the profit margin between the FPO or SHG and the cold room users, ensuring that both parties benefit from improved prices. Alternatively, a fixed processing fee may be deducted, and the remaining margin is returned to the farmers, providing them with a stable income. Another option is to guarantee a specific price for the

produce, with any surplus margin staying with the FPO or SHG. This approach closely resembles option (a) outlined earlier but doesn't entail the upfront sale of produce by farmers to the FPO or SHG. The Custody Model offers flexibility and potential for stable income while farmers await favorable market conditions.

Community-based groups enhance the efficiency and effectiveness of the supply chain for farmers by reducing malpractices and transaction costs, facilitating connections with various commercial institutions such as traders, processors, and retailers, marketing agricultural outputs, obtaining crucial market information, and strengthening farmers' bargaining power through collectivisation. Leveraging market price forecasts available on Coldtivate and other platforms, FPOs and SHGs can potentially sell aggregated produce at rates surpassing the market average. The stable revenue stream generated by offering CaaS enables these community-based groups to effectively cover the costs associated with operating and maintaining the cold rooms. An additional advantage of involving community-based groups, particularly FPOs, lies in the vested interest of farmers and their representatives to ensure the proper upkeep of the cold rooms. This stands in contrast to many centralised cold rooms, which often fall into disrepair due to neglect.

Local cooling companies and entrepreneurs can empower community-based servitisation through comprehensive training sessions that cover technical aspects like cold room operation and maintenance, as well as non-technical aspects like user registration and billing. To leverage the power of community networks for awareness and skill-building, trainers can establish peer-to-peer learning programs, where participants of similar levels or professions engage in collaborative education. As trained farmers share their knowledge with their peers, the benefits of cooling can reach a wider audience. Cold room manufacturers typically provide maintenance services until the warranty expires. Beyond this period, local youth with technical qualifications can undergo training from cooling companies to troubleshoot and conduct routine checks on the cold room's systems.

## 3.4 MANAGING COLD ROOM OPERATIONS UNDER CAAS

### 3.4.1 Checklist for Cold Room Site Selection

There are several key factors to consider when selecting the technology and site for a cold storage facility:

- i) **Location:** The chosen location should be easily accessible and in proximity to market hubs or produce collection points. Accessibility to road networks is particularly important.
- ii) **Electricity:** A reliable and uninterrupted power supply is essential for the efficient operation of the cold storage facility. The availability of electricity directly impacts the facility's size and equipment selection.
- iii) **Drainage and Waste Disposal:** Adequate drainage options and waste management equipment should be readily available at the site.
- iv) **Water Supply:** Ensuring a dependable water supply and proper wastewater removal are essential for maintaining the functionality and sanitation of the cold storage facility.
- v) **Economic Viability:** The value generated from cold storage must justify both ongoing operational expenses and future investments in the facility.

### 3.4.2 Tips to onboard new users

Local cooling companies or community-based groups are encouraged to conduct training sessions to educate potential users about the benefits of cold storage. These sessions should cover topics such as the operating hours of the cold storage units, the types of crops that can be stored, and the associated tariffs. Establishing trust in the advantages of cold storage for preserving food quality and obtaining better market prices is essential for attracting the initial customer base. For this, farmers could be allowed to utilise the cold rooms for free for a set duration wherein they store a portion. To achieve this, farmers can be offered a limited free

trial period during which they can use the cold rooms to store a portion of their crops at ambient temperature. This hands-on experience allows farmers to witness firsthand the benefits of cooling, including reduced softening, wilting, and mold development in comparison to uncooled produce. Workshops for such experiments are best held in inclusive public spaces accessible to people of all backgrounds. Additionally, setting up registration booths to issue identity cards and unique identification numbers to cooling users has proven effective in generating interest among farmers and enhancing the solution's credibility, as demonstrated in the Your VCCA pilots.

In addition to teaching users about the benefits of cooling for longer produce shelf life, such training sessions are crucial for fostering trust within community-based organisations. Collective crop marketing through FPOs can result in better prices for members, even in volatile markets. However, this opportunity is often lost as smallholders tend to sell their crops individually to intermediaries at their farms. Research shows that group training reduces opportunistic behavior among members and enhances trust in the integrity, information-sharing abilities, and negotiation skills of the group's leaders. This helps overcome barriers to crop aggregation and establishing connections to forward markets.<sup>26</sup>

During this stage, cooling companies should gather gender-disaggregated data regarding the types of crops cultivated in the region and the average prices farmers receive for them. It's essential to identify which crops are most likely to benefit from cold storage and understand the factors that might hamper its use. This can be investigated through methods such as focus group discussions, mixed-method interviews, and quantitative surveys supplemented with qualitative questions. Community champions or local producer organisations can facilitate this process. After analysing the survey or interview results, user engagement strategies can be customised to meet local requirements, with a focus on promoting cold storage for specific crops grown in the area. Additionally, this data can serve as a baseline for assessing the impact of decentralised cooling on increasing smallholder incomes.



### 3.4.3 Tips for checking-in crates

#### i) Pre-cooling

The preliminary or pre-cooling of freshly harvested crops before their transfer into cold rooms limits the respiratory activity of the harvest, thereby preserving the weight and quality of the produce. Pre-cooling involves the removal of field heat from fruits and vegetables, which is the temperature difference between their actual temperature and the optimal storage temperature. As outlined in **Table 3.1**, this can be achieved through methods such as room cooling, forced air cooling, water spraying, ice packaging, hydrocooling, and vacuum cooling. In cases where pre-cooling options are unavailable, farmers should be encouraged to utilise passive cooling techniques on their farms, as detailed in **Chapter 1, section 1.3.2**. To reduce the immediate need for pre-cooling, harvesting can also be scheduled during the early morning hours to take advantage of lower temperatures. Pre-cooling proves especially advantageous for farmers selling their crops in distant regional markets, as it diminishes the susceptibility of

crops to bruising from transport vibrations and reduces the need for refrigeration during transit from the farm to cold rooms or markets.<sup>27</sup>

Pre-cooling is regarded as the most cost-efficient and efficient value-adding practice in the horticultural chain. In ambient temperatures of above 35 °C, pre-cooling should be performed within an hour of harvest.<sup>28</sup> Otherwise, the harvest is likely to suffer a loss in storage life of about one day, even if it is placed under optimal storage conditions later. For every 10 °C rise in the temperature, the rate of food decay is likely to multiply by two to three times.<sup>29</sup>

As a general guideline, fruits and vegetables with soft or fleshy outer layers, such as berries, grapes, tomatoes, stone fruits, capsicum, chili peppers, eggplant, cucumbers, green beans, peas, and spinach, should undergo rapid pre-cooling. On the other hand, those with relatively harder outer layers, such as papaya, guava, green bananas, pomegranates, radish, cabbage, cauliflower, and carrots, can achieve proper storage conditions even without pre-cooling.

**Table 3.1.** Pre-cooling Methods for different crop types.<sup>30,31</sup>

TABLE 3.1		
Method	Description	Crops to use the method on
Room Cooling	A low to no cost method that requires placing crops in a room with a fan passing cold air.	Beetroot, cabbage, peppers, pumpkins, squash, tomatoes, zucchini
Air Pre-cooling	A common way of reducing the temperature of fruits using cold air in a storage room, refrigerator car, tunnel, or forced air cooler.	Mainly fruits
Forced-air cooling	A method that involves passing cold air through the crates at high velocity is used to lower the crops to their lowest safe storage temperature. However, forced-air cooling exposes crops to the risk of extreme dryness due to moisture loss.	Beans, brussel sprouts, cabbages, carrots, cauliflower, celery, cucumbers, kohlrabi, leafy greens, lettuce, peas, peppers, potatoes, raspberries, spinach, rhubarb, strawberries
Icing	Ice is used to cool down product in packed boxes. Crushed ice can also be placed directly on top of crops.	Asparagus, broccoli, leeks, green onions, parsnips, radishes, rutabaga, sweet corn.
Hydrocooling	A fast method to cool and clean crops by submerging them in cold water. It is important to use a heat exchanger to ensure that the water temperature remains low at all times. This method is most commonly used to precool vegetables.	Asparagus, beans, broccoli, carrots, cucumbers, kohlrabi, parsnips, radishes, rhubarb, rutabagas, sweet corn
Vacuum cooling	A method best suited for crops without thick cuticular wax coating (outermost layer that covers a fruit or vegetable's outermost cells). Crops cool down quickly due to the evacuation of air, which causes a rapid evaporation of water located at the surface of the crops. A disadvantage of this method is that it reduces the crop weight of the crop by 1% for every 5-6 °C reduction in temperature.	Lettuce, leeks, Chinese cabbage

### ii) Baseline survey and impact evaluation through Coldtivate

Companies are strongly encouraged to conduct a baseline survey integrated into Coldtivate to gather user data, with a specific focus on gender disaggregation, whenever a new user joins the platform. Additionally, cooling users are requested to periodically participate in post-usage surveys aimed at tracking the progress in reducing their post-harvest losses. Operators can remind cooling users to complete these surveys during their visits to the cold room. Collecting data consistently over time enables cooling companies to assess their operational impact, including the extent to which they have contributed to increasing farmer incomes.

### iii) From baskets to crates

The next step involves separating the products by type, size, and quality into different crates. Products should be transferred to well-vented and stackable crates, replacing the baskets or cardboard boxes brought in by the users.

During the transfer from the farmers' baskets to the company's crates, the operator should assist users in removing soil, pebbles, and loose plant material like wilted leaves and twigs from the produce. Any damaged, bruised, infected, or over-mature produce should be properly discarded in a compost. All items must be dry before placement in the crate and inside the cooling room to prevent bacterial growth.

Crates should be filled efficiently but not overfilled, leaving a 10 cm buffer space from the top for air circulation. Details like the farmer's name, the number of crates stored, the type of commodity, the intended storage duration, and the harvest date should be registered by the operator on the Coldtivate app. A tag with the farmer's name and check-in date can be affixed to the crate to prevent mixing and customer confusion. This information is also visible to farmers for transparency. If any registration errors are identified, farmers should promptly notify the operator, who can edit the app to ensure accurate information.

### iv) Check-in the crates on Coldtivate

Currently, most rooms rely on manual registers to keep track of the inflow of new commodities into the room. Once the crates brought in by a farmer are assembled in the room, the operator writes down the number of crates and the type of commodity stored. Although sufficient to get by, such a process could be more efficient and less prone to mix-ups. When the same user brings in commodities harvested on different dates, it is difficult to determine which crates need to be withdrawn first before the crop spoils. Similarly, multiple and frequent check-ins and check-outs within a day make it difficult for operators to efficiently calculate the amount owed by each user.





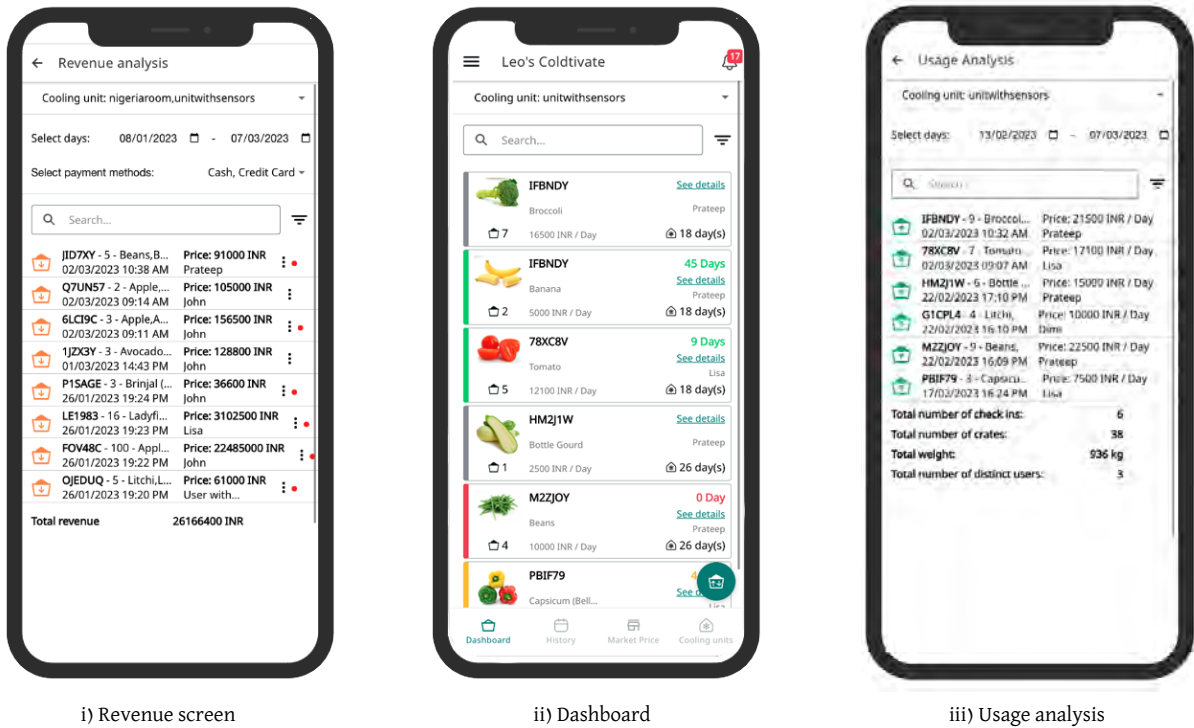
Coldtivate was designed to function as a remote inventory management tool. When a user brings their crops to the cold room, the operator can digitally record the number of crates and the type of commodity. Beyond simply documenting the new commodities, Coldtivate calculates how these additions impact the room's total occupancy rate and the distribution of different fruits and vegetables. This summary of crop composition enables the operator to make well-informed decisions about the ideal temperature range for the crops currently in storage, with reference to temperature charts available both in this manual and within Coldtivate's Knowledge Hub.

Before the crops are checked in, the app prompts the operator to weigh the crates and assess the produce's quality based on the day of harvest provided by the farmer. These initial quality checks, combined with real-time sensor data from the room, are used to predict the storage life of each crate of produce. Cooling users are then notified about which crates need to be withdrawn first based on their remaining storage life. During check-in, farmers also specify how long they plan to keep their crates, which allows the app to provide an overview of the room's occupancy rates in the upcoming days. This information enables operators to advise farmers on when and how much to harvest in the coming days to ensure timely and adequate cooling.

The app provides three types of room summaries:

- **Financial Summary:** This section, illustrated in **Figure 3.2 (i)**, displays monthly records of the payments made by farmers and the total revenue generated for each cold room during a specific time period. Operators and registered employees can easily access this financial information on one screen.
- **Storage Life Summary:** **Figure 3.2 (ii)** shows the storage life summary, which lists the crates currently stored in a room. It includes details about the cooling users to whom these crates belong and the remaining storage life of each set of crates. The remaining storage life is color-coded for quick reference: red (pick-up within the next 2 days), yellow (pick-up within the next 2-5 days), green (more than 5 days to pick-up), and grey (no information available about the pick-up time). Operators can use this information to notify farmers marked in red to check out and sell their crops within the next few days, particularly useful for farmers without smartphones.
- **Usage Analysis Dashboard:** Displayed in **Figure 3.2 (iii)**, the usage analysis dashboard consolidates data on the total number of check-ins and users per room and time period. This dashboard provides an overview of room utilisation and user activity.

Figure 3.2: Summary screens available on Coldtivate to monitor each cold room's performance.



v) Stacking the crates

A standard crate with a 25 kg capacity should ideally only hold between 20 to 23 kgs of produce. These crates should not be stacked directly against each other; instead, there should be a small buffer space of 5 to 10 cm to allow airflow in and around the crates. This buffer space ensures proper ventilation and prevents the easy spread of microbial spoilage to other crates. Similarly, crates should be positioned at a distance of 10 to 15 cm away from the walls of the cold room to avoid chilling injury.

Chilling injury (CI) refers to physiological damage that affects crops stored at low but non-freezing temperatures. It can result in issues like tissue browning, wilting, pitting, soggy breakdown, uneven ripening, and the development of off-flavours. CI is most common in crops of tropical and subtropical origins, such as bananas, citrus fruits, tomatoes, and peppers, which have low or no tolerance to cold temperatures. However, it's worth noting that even crops like apples, which thrive in cold climates, can be chill-sensitive, with some varieties being more susceptible than others.

Table 3.2 on the next page provides an overview of the susceptibility to CI among major vegetable types.







Table 3.2: Vegetables susceptible to chilling injury <sup>34,35</sup> at moderately low but non-freezing temperatures

Commodity	Lowest Safe Temperature (° C)	Symptoms	Healthy	Damaged
Avocados	12	Pitting, brown or black discoloration, bitterness, rancidity		
Bananas	13	Darkening of skin, poor ripening		
Beans (Snap)	7	Pitting and russeting		
Cucumbers	10	Pitting, water-soaked spots, decay		
Citrus				
- Grapefruit	15	Pitting, browning, watery breakdown, decay		
- Lemon	10	Pitting, membrane staining, red blotches		
- Lime	7	Pitting		
Eggplant	7	Surface scald, pitting, increased decay		
Mango	12	Dull skin, brown areas		
Melons				
- Cantaloupes	5	Pitting, surface decay		
- Honeydew	7 to 10	Pitting, failure to ripen		
- Casaba	7 to 10	Pitting, surface decay		
- Crenshaw and Persian	7 to 10	Pitting, surface decay		
Watermelons	4	Pitting, objectionable flavour		
Okra	7	Discoloration, water-soaked areas, pitting, decay		
Papaya	7	Pitting, water-soaked areas		
Peppers (sweet)	7	Sheet pitting, Alternaria or surface rot on pods and calyxes		

Table 3.2: Vegetables susceptible to chilling injury <sup>34,35</sup> at moderately low but nonfreezing temperatures

Commodity	Lowest Safe Temperature (°C)	Symptoms	Healthy	Damaged
Pineapple	10	Brown or black flesh		
Potatoes	3 to 4	Mahogany browning, sweetening		
Pumpkin and hard shell squash	10	Decay, especially alternaria rot		
Sweet Potatoes	13	Decay, pitting, internal discoloration		
Tomatoes				
- Ripe	10	Water soaking and softening decay		
- Mature Green	13	Poor colour when ripe, Alternaria rot		

In many cases, CIs may only become detectable when the produce is removed from the cold room for distribution. To facilitate the recovery of fruits and vegetables from heat-induced damage, it is essential to store them below the recommended temperature for the specified duration. Exceeding this timeframe could result in chilling injuries. Prolonged exposure to low temperatures can induce irreversible damage. Therefore, the most common preventive measures for CIs are high temperature treatments and intermittent warming.

#### a) High temperature treatments

Short-term high-temperature treatments, including methods like hot water dips, hot water brushing, and hot humid air conditioning, have demonstrated effectiveness in reducing chilling injuries and fungal infections in various vegetables and fruits. These treatments vary in terms of duration and temperature range. Hot water dips typically involve a few minutes of exposure to high temperatures. For instance, citrus fruits are subjected to 2–3 minutes at 50–53 °C to control fungal growth.

On the other hand, hot air treatment lasts 2–3 days at milder temperatures, with citrus benefiting from 3 days at 38 °C.<sup>36</sup> Timing is crucial when considering these treatments, especially since crops brought into cold rooms might have already endured prolonged exposure to heat. These treatments are effective when room temperatures must be significantly lowered to accommodate one crop, potentially falling below the safe limit for another crop, which then requires high-temperature treatment.

#### b) Intermittent Warming

Intermittent warming (IW) is a post-harvest treatment that involves one or more warming periods during cold storage to maintain fruit quality.<sup>37</sup> IW enhances the long-term storage of various fruits and crops, such as citrus, mango, and eggplant.<sup>38</sup>

In theory, IW is an ideal technique to reduce CI, but implementing and optimizing an IW regimen on a commercial scale can be challenging.<sup>39</sup>



## vi) Maintaining the cold room

### a) Use plastic curtains on doors to reduce loss of cold air

Opening the door of a cold room displaces the cold air, allowing warmer air to enter. These fluctuations lead to condensation, ice accumulation, and energy loss. Implementing a barrier that restricts the exchange of warm and cold air reduces energy consumption in maintaining the desired cold room temperature. This barrier helps maintain a consistent air temperature, thus extending the shelf life of stored products. Reduced moisture due to decreased condensation also minimises the opportunity for bacterial growth. Ice buildup resulting from temperature shifts can create slippery surfaces, posing health and safety risks. Moreover, even if the door is inadvertently left open for an extended period, such as in cases of forgotten doors that are challenging to monitor, the impact on food safety is minimised.



### b) Keep high relative humidity in the cold rooms

Unchecked humidity can lead to condensation, frost, and ice buildup in a cold room. While some humidity will always enter a cold room, it can largely be controlled. Elevating relative humidity helps prevent moisture loss and maintains product quality and weight. Dealing with day-to-day condensation and ice buildup issues involves understanding how humidity affects cold rooms.

When air enters a cold storage, its moisture decreases as the temperature drops below the dew point, which is the temperature at which the air holds as much moisture as possible. Further cooling causes water droplets to form on surfaces, especially on the refrigeration system's coils. As the air circulates within the cold storage, it warms up, reducing its relative humidity. Warm air can hold more water vapor than cooler air. The warm air draws this extra moisture from various surfaces, including the stored items, leading to weight loss in the crops and a loss of firmness at the cellular level.

The reason behind this moisture absorption is that air tends to equalise moisture levels. When air with lower relative humidity encounters surfaces or products with higher moisture content, it draws



moisture from those surfaces to achieve equilibrium. This process reduces the weight of the crops and impacts their cellular structure, leading to a decline in product quality, visual appearance, and shelf life. These factors diminish the health and monetary value of the stored stock.

To prevent moisture loss, it's essential to maintain relative humidity at levels in equilibrium with the stored produce. Optimal conditions vary depending on the type of fruits, vegetables, flowers, or other products stored. Generally, a humidity level of around 95 percent relative humidity (RH) is necessary at a temperature slightly above freezing. Even in warmer storage environments, a humidity level of approximately 75 percent RH benefits the produce.<sup>40</sup> To achieve the required moisture, it should be introduced directly into the air and evenly distributed throughout the storage area. Implementing direct room humidification ensures consistent humidity levels, preserving the quality of the stored produce.

#### vii) Sanitation measures

To ensure the stored produce remains safe and fit for consumption, it is vital to keep the cold room clean and perform preventive maintenance regularly. Cold room operators can employ vacuum cleaners or scrubber dryers along with mild cleaning agents or specialised cold room cleaning products to remove dirt that may enter the cold room with the crates. Regular cleaning is essential because organic grime can freeze and accumulate in crevices.

Before using any cleaning agent, it is important to properly cover all open crates to prevent aerosols (fine solid particles or liquid droplets suspended in the air) from settling on the produce. It is advisable to clean the room when it is relatively empty or entirely empty. During this time, the cooling mechanism can be switched off, allowing operators to use water and sufficient cleaning agents. High-pressure washers can be used without the risk of water freezing in these conditions.

While cleaning, operators should also inspect crates for spoiled products and promptly remove them to prevent bacterial growth. Once the cleaning is complete, the room should be left to dry thoroughly to prevent frozen and slippery floors.

#### viii) Checking-out the produce in cold room

Coldtivate provides operators with the flexibility to select the specific crate(s) that the farmer intends to check out. This digitalised check-out process proves invaluable, particularly when storing prices vary for different types of crops. It simplifies the calculation of the amount owed by each user, enhancing transparency and reducing the likelihood of payment disputes. Additionally, cooling companies operating in multiple locations can access an overview of the total revenue generated per room.

In situations where cooling users do not possess smartphones, operators should employ alternative methods to remind them of upcoming pick-up dates for their crates. These reminders can be delivered through SMS, phone calls, or in-person communication. **Timely notifications should be sent when there are two weeks, five days, and two days of storage life remaining.** It is important to note that the same farmer may have multiple crates stored in the room, each containing different types of crops with varying check-in dates. These variables impact the remaining storage life and room temperature for each crate, underscoring the necessity of informing farmers about each of their crates at these three key points.

Following the check-out of crates, operators should actively encourage cooling users to participate in a post-checkout market survey. This survey is designed to gather data on where and at what price the stored crops were sold. Such information is essential for cooling companies to assess whether their services have helped farmers secure better prices for their produce. Specifically, it helps determine whether farmers received higher prices compared to their pre-cold room use or in comparison to non-users as identified during the baseline surveys. This data-driven approach is crucial for evaluating the impact and effectiveness of cold storage solutions in improving farmers' income and overall livelihoods.







## Chapter 04

# MAINTAINING SOLAR-POWERED COLD ROOMS

Solar-powered cold rooms represent a sustainable and efficient solution for preserving perishable goods. To uphold their optimal performance and longevity, regular maintenance of the solar panels is of utmost importance. Simultaneously, maintaining a clean and sanitary environment within the cold rooms is equally critical to prevent contamination, spoilage, and the proliferation of harmful bacteria. This chapter provides recommendations for the preventive maintenance of various cold room components and offers straightforward solutions for common issues. **Nevertheless, it is essential to regard this chapter as a 'first response' guide rather than the ultimate remedy. In cases where a problem persists, it is advisable to promptly seek the assistance of a technician to ensure the safety and quality of the stored products.**

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## 4.1 Tips for maintaining different parts of the cold room

Item	Image	Activities
Solar Panel		<ul style="list-style-type: none"> <li>• Clean the panels using a soft-bristled brush or cloth with fresh water (Total dissolved solids &lt; 1500 mg/L), avoiding harsh chemicals or abrasive materials to prevent scratching.</li> <li>• Perform cleaning every 15 days to maintain panel efficiency.</li> <li>• Note the daily and monthly generation levels and address any discrepancies in low generation through cleaning, removing shadow effects, checking loose wiring connections, and decarbonising connection ends as needed.</li> <li>• Regularly inspect panels for physical damage like cracks or chips and address promptly to prevent further harm.</li> <li>• Check for loose connections between solar panels and the cold room's refrigeration unit to maintain system efficiency and ensure safety.</li> <li>• Periodically inspect the area around the solar panels and trim any trees or vegetation that may block sunlight. Consider relocating panels if shading persists.</li> </ul>
Compressor		<ul style="list-style-type: none"> <li>• Regularly clean the compressor to keep it free from dirt and debris. Use a soft cloth or brush to remove any accumulated dirt. Turn off the power before cleaning.</li> <li>• Ensure there are no oil or refrigerant leakages from the compressor.</li> <li>• Check the refrigerant cooling level to maintain optimal performance.</li> <li>• Keep the compressor cool by ensuring proper airflow and removing any obstructions around it.</li> <li>• Verify that the compressor discharge pressure and suction pressure are within the recommended limits.</li> <li>• Periodically replace the compressor air filter to maintain clean airflow. Dirty filters can affect compressor efficiency.</li> <li>• Check the voltage and current values at the compressor terminal, ensuring they fall within acceptable ranges.</li> <li>• Ensure tight and secure electrical and refrigerant connections for reliable operation.</li> </ul>
Evaporator		<ul style="list-style-type: none"> <li>• Clean the evaporator and fins.</li> <li>• Clean the evaporator casing and all blowing fans.</li> <li>• Check the temperature sensors that regulate the cold room's temperature.</li> <li>• Check for any ice formation in the evaporator.</li> </ul>
Batteries		<ul style="list-style-type: none"> <li>• Batteries should always be kept clean and free from dirt and corrosion.</li> <li>• Batteries should be filled with distilled water only, and the water level should be checked according to indicators provided by the manufacturer.</li> <li>• Any carbon buildup at battery terminals should be removed to avoid low battery charging and discharging.</li> <li>• Regular inspection of batteries is essential to ensure they are in good condition. Check for any signs of damage, such as cracks or bulges, and ensure that the battery terminals are clean and free of corrosion.</li> <li>• Ensure that the batteries are properly charged to maintain their performance and prolong their lifespan. Check the manufacturer's recommendations for charging procedures and make sure to follow them.</li> </ul>

### 4.1 Tips for maintaining different parts of the cold room

Item	Reference	Activities
		<ul style="list-style-type: none"> <li>• Carry out periodic equalising. Equalising is a process that helps to balance the voltage levels of individual cells in a battery. This process can help to prolong the life of the battery and maintain its performance.</li> <li>• Batteries are sensitive to temperature changes, and extreme temperatures can affect their performance and lifespan. Ensure that the batteries are installed in a location that is protected from extreme temperatures, and that the cold room is well-ventilated to prevent overheating.</li> </ul>
Refrigerant circuit		<ul style="list-style-type: none"> <li>• Periodically check the refrigerant circuit pipe for any leakage.</li> </ul>
Control system		<ul style="list-style-type: none"> <li>• Verify the functionality of the defrosting function.</li> <li>• Ensure the control valves are operating properly.</li> </ul>
Insulation system		<ul style="list-style-type: none"> <li>• Inspect the roof and walls for any signs of leakage and promptly address any identified issues.</li> <li>• Verify the locking mechanisms of the door to prevent ambient air infiltration into the cold room.</li> </ul>
Sensors		<ul style="list-style-type: none"> <li>• Perform regular checks on the humidity and temperature sensors to ensure their accuracy and functionality.</li> <li>• Calibrate the cold room temperature monthly to maintain precise temperature control.</li> <li>• Regularly monitor the temperature of the cold room when it is fully loaded.</li> <li>• Regularly assess the sensor performance to ensure accurate readings. Compare the sensor readings with recommended levels for the specific products stored in the cold room.</li> </ul>
Overall Sanitation		<ul style="list-style-type: none"> <li>• Ensure cleanliness of the storage space.</li> <li>• Mop the floor every three days to remove any foreign particles.</li> <li>• Restrict access to the cold room without permission from the relevant authority.</li> <li>• Promptly address and wipe out any water leakage, preventing contact with stored commodities.</li> <li>• Notify the technical team to address any water leakage issues inside the cold room.</li> <li>• Use a vacuum cleaner to regularly remove dust accumulation on the floor (every two days).</li> <li>• Clean up any spillages immediately.</li> <li>• Organise the crates neatly at the end of each day as needed.</li> </ul>



### 4.2 Emergency Response to Technical Difficulties in the Cold Storage

Challenge	Solution
Water ingress into the cold room	To prevent water ingress into the cold room, it is crucial to thoroughly inspect all internal piping, piping joints, and roof panel joints. If any issues are identified, they should be addressed promptly. In cases where the problem persists, it is recommended to promptly notify the cooling system manufacturer to replace any leaking pipes.
Condensation within the room causes excessive water on the floor	To mitigate the impact of high-humidity weather conditions, it is important to keep the cold room doors closed or limit their operation to minimise the infiltration of humid air into the cold chamber. Additionally, operators should refrain from placing crates filled with commodities directly below the evaporator to prevent any potential water from falling into them. These measures help maintain optimal conditions and protect the quality of stored goods.
Difficult to determine room temperature for multi-commodity cold rooms	To extend the shelf life of commodities, operators should adhere to a temperature-commodity chart and establish the appropriate temperature range to maintain within the cold room. By carefully monitoring and maintaining the recommended temperature levels, the quality and longevity of the stored commodities can be significantly improved.
Risk of the compressor unit tripping from the cold room's overutilisation	To avoid excessive strain on the cold room, it is important to prevent overutilisation of the available space. Continuous operation of the compressor for extended periods should be minimised. Additionally, installing lighting arrestors or protective devices is recommended to prevent any overcharging of current to the cold room's components. These measures help maintain the efficient and safe functioning of the cold room.
Short circuit in the thermal battery charger	During summer, it is possible for the fan wire inside the solar battery charger to overheat and malfunction. To address this issue, it is recommended to consult a technician who can adjust the fan wire's connection to approximately 24 volts. This adjustment allows the fan to operate directly and helps dissipate excess heat from the solar battery charger. Not only does this prevent overheating, but it also enhances the overall performance of the charging unit.
Risk of operators getting trapped in the cold room	Regular inspection of the internal door openings is necessary, and any malfunctions should be promptly reported to the cold room's technical team. Timely reporting ensures that any issues with the door openings can be addressed promptly, maintaining the proper functioning and integrity of the cold room.





## Chapter 05

# HOW CAN YOU START USING COLDTIVATE?

Coldtivate is a **free-to-use, data science-based mobile application** that caters to cooling companies, operators, and users, enabling them to transition from manual registers to efficiently managing rooms and monitoring the quality of stored crops on their phones.

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## 5.1 HOW CAN YOU JOIN COLDTIVATE?

**Cooling companies, cold room operators, FPOs, farmers and traders can register for free on Coldtivate.**

**Cooling companies:** The first registered employee (RE) of the cooling company, typically from the management team, that signs up to Coldtivate should **'Sign up as company'**, where both the company and the user are registered. Once registered, the RE can sign in and invite other REs and operators to join the company. All registered employees have the same permissions within the app, regardless of whether they were the initial RE or invited later. To invite other registered employees, go to the **Management → Registered Employees** section. Click on the '+' sign to send a registration link via SMS to their phone numbers.

**Operators:** In the context of the Your VCCA project, we define operators as the persons physically present at the cold room premises, who manage the interactions with the cooling users, perform check-in and check-out operations at the rooms, and collect storage fees.

Depending on the project configuration, operators could be employees of the cooling company, members of a farmer producer organisation, a farmers' cooperative society, a self-help group, or an independent farmer or trader hired from the local community to run the rooms (see **Chapter 3, Section 3.1.3** for more information).

For simplicity, in Coldtivate, this user type is assumed to be linked to the company maintaining the cold room and thus needs to be invited by a registered employee to join the company in the app. Operators can sign up following an invitation URL sent by SMS with a phone number (no email needed).

**Cooling users:** Smallholder farmers and small-scale traders can sign up on Coldtivate independently of any cooling company, if they have access to a smartphone. In the welcome screen, they can click on **'Sign up as a cooling user'** and provide their phone number and other personal information to register. This allows them to log in and locate cold rooms in their vicinity to start benefiting from cold storage. Farmers and traders without access to a smartphone can be registered in the app by the operator of the first room where their crates are being checked in, using their phone number as identifier. For users without a phone number, the operator can record check-ins and check-out for a generic user, named **'User without a phone'**.



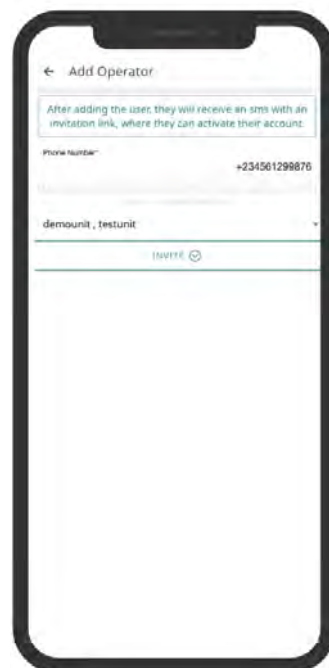


## 5.2 WHAT ARE THE MAIN FUNCTIONALITIES OF COLDTIVATE?

Coldtivate enables cooling companies to digitally manage the inventory of each of their cold rooms and remotely monitor room occupancy, finances, and temperature. Simultaneously, the app empowers farmers to track the remaining quality of their stored produce, monitor cold room conditions, and access information on post-harvest best practices.

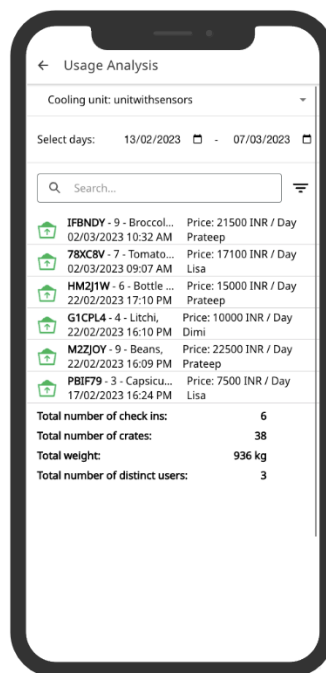
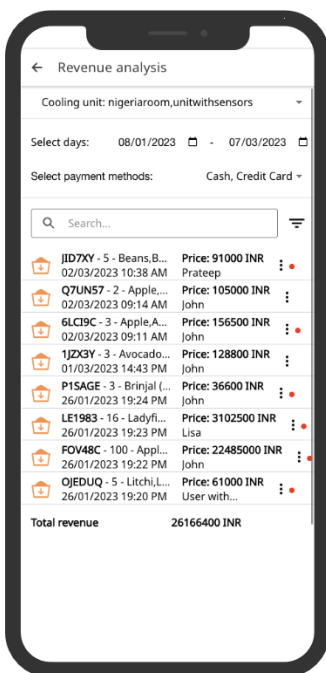


i) The primary responsibilities of registered employees include setting up the cooling units on the app, inviting other REs and operators to join, and assigning operators to specific cold rooms. To add cooling units, navigate to the **Management → Cooling Unit** section. Additionally, REs must add the geographical location of each room under **Management → Location**. This step is crucial for distinguishing between multiple units situated in the same market. If temperature sensors are present in the cold rooms, they can be linked to Coldtivate as a cooling unit property (as shown in the image).

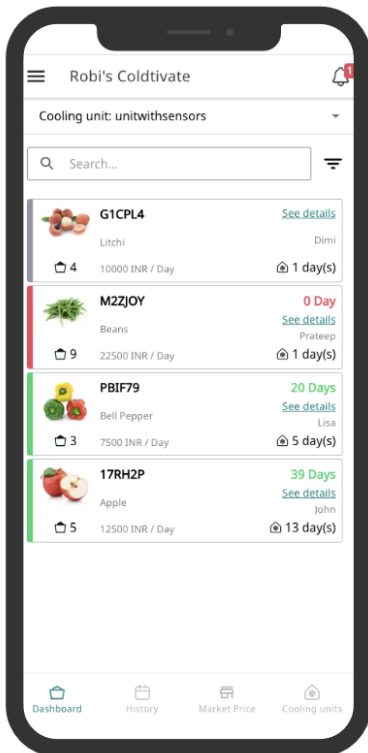


ii) All registered employees of the company can manage the assignment of operators to cold rooms. To invite operators to join a cooling company, navigate to the **Management → Operators** section in the menu and click the '+' sign. An automatic invitation link will be sent via SMS to their respective phone numbers.

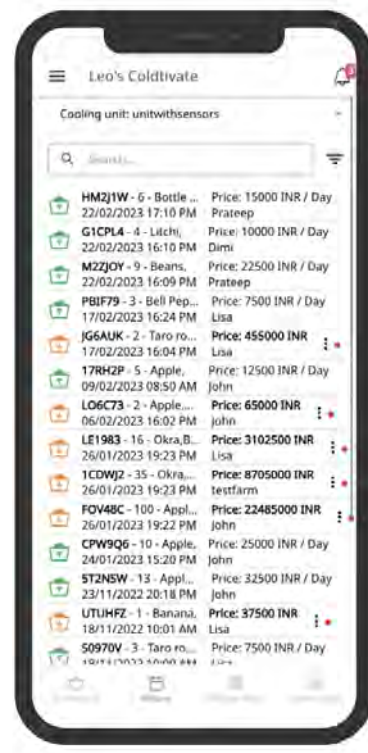
Operators can be assigned to cold rooms during the invitation process by editing the **Operators** field on the **Cooling Unit** page. Alternatively, assignments can be made by editing the **Cooling Unit list** on the **Operators** page. It is important to note that operators can only monitor and perform check-ins and check-outs in rooms to which they have been specifically assigned.



iii) The **Revenue Analysis** option under the **Management** menu allows REs and operators to assess the total revenue generated during a specific time frame for one or multiple cooling rooms. On the other hand, the **Usage Analysis** feature provides an overview of the number of check-ins, users, and crates for one or multiple cooling rooms within a given period.

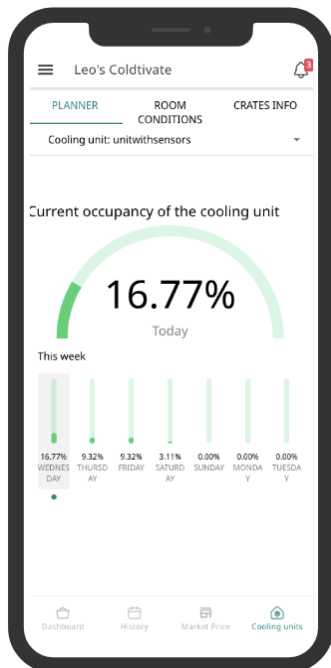


iv) The crates currently in storage in a cooling unit can be seen by selecting a cooling unit from the dropdown in the **Dashboard** menu. Each crate's information includes the user's name, crop type, pricing scheme, days in storage, and the remaining days until the specified time-to-pick-up (TTPU), indicated by a colour code. Green indicates more than 5 days remaining for TTPU, yellow signifies TTPU within the next 2-5 days, and red suggests TTPU within the next 2 days. The colour can be grey for crops without a digital twin (DT) or if the DT model is deactivated for the company. Clicking on each card provides additional details about the stored crates and the cooling user's contact information, if necessary. The page also offers a search and sort option to quickly find specific crates of interest. Each cooling user can only visualise their own crates in storage in the **Dashboard**, whereas the operators and RE have full visibility on all crates currently stored by different users in a given day.

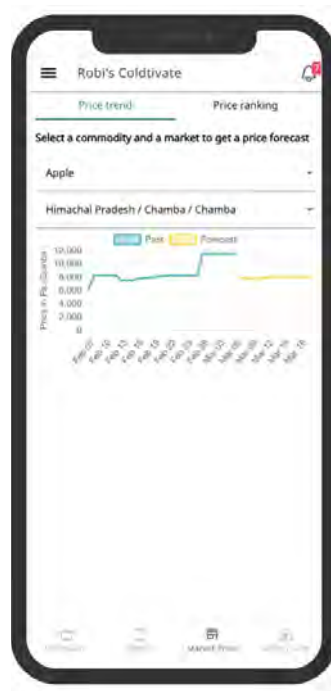


v) All users can use the **History** tab to select a cooling unit, track all past crate movements (check-ins and check-outs), and download receipts for crates that have been withdrawn. Check-ins will be displayed in green (representing arrivals), while check-outs will be showcased in orange (indicating departures). Additionally, you can effortlessly monitor the corresponding fees owed, ensuring a comprehensive overview of the financial aspect tied to each crate. As for the **Dashboard**, cooling users only see movements they have undertaken, while operators and REs can view all operations performed in a given room.





vi) Under the **Cooling Units** section, users can visualise the current and predicted occupancy for each room they are linked to (in the **Planner** tab), the room temperature in the last 7 days (in the **Room conditions** tab), and summary statistics of all crates in storage organised per crop type and weight (in the **Crates info** tab; this is only available to RE and operators). In the **Maps** tab, cooling users can explore cold rooms in their vicinity.



vii) By navigating to the **Market Price** tab, users can visualise historical and forecasted market prices for different commodities. The historical prices are extracted from country-specific open-source data, whereas the forecasts are the output of a machine learning model that is regularly updated to reflect the latest market trends. This feature is only available in select countries.



### 5.3 COLDTIVATE'S STORAGE LIFE MODEL

Fruit and vegetables are living products. Even after harvest, they keep on 'breathing' or respiring. As a result, the quality of the product decreases, changing from a fresh crop at harvest to an overripe crop during post-harvest storage.

The past decades, many supply chain stakeholders have measured how different crops behave or deteriorate at different storage temperatures. Using this data, mathematical models, called 'Shelf life models' have been established to predict the quality of the crop over time when displayed on a shelf, e.g. a shelf in the supermarket or local market, based on the temperature.

**Shelf life models are a key component of the Coldtivate app:** by providing regularly updated information about the remaining storage life of each crate stored in the cold room, they help cooling users to understand for how long their produce is still good for, and thus drive their decisions on the best selling time. The storability of fruits and vegetables is affected by temperature conditions during cold storage. Due to the thermal sensitive nature of fresh food, they decay gradually during long storage to a certain quality threshold, below which the product is not acceptable anymore to the consumer. Most of the temperature-induced underlying biochemical reactions responsible for quality changes of fruits and vegetables can be adequately modelled using a kinetic rate model.

A kinetic rate model is a simple mathematical expression that predicts the reduction in the quality attribute of a product per unit time. Hence, based on the temperature history, the remaining quality of each product can be calculated during storage taking into account the crop type and initial quality of the crop at check-in.

**The term 'storage life' refers to the duration a product can be stored before it reaches the quality threshold for consumption.** Since this prediction involves the future, Coldtivate's kinetic models for storage life calculations use the expected temperature inside the cold room, which is the room's set temperature, rather than sensor data.

**On the other hand, 'shelf life' is similar to 'storage life' but pertains to a product's storability after storage when it is displayed on a shelf or market under uncontrolled ambient conditions.** The temperature used in the 'shelf life' model is higher and matches the environmental temperature.

In Coldtivate, the projected check-out date for each crate displays the **'time-to-pick-up' (TTPU)**, which estimates storage life while maintaining a minimum shelf life of 0.5 days at an environmental temperature of 30 °C. This ensures that sufficient time is available to transport the products to the market and sell them after they are taken out of storage.

**When calculating the TTPU, the following considerations are taken into account:**

i) Fruit and vegetables are living products which are subjected to biological variability. Due to this biological variability, every product will respond differently. For example, every product has its own size and shape, but even when you take 2 products which look similar and are harvested at the same farm, they can still show different storage lives. The digital twin model is a virtual representation to calculate and predict how the real crop is behaving 'on average'.

So, the general message here is that you have to interpret the TTPU with care. When the TTPU is indicated as 5 days in the app, it could be that some products in the crates will have a TTPU of 4 or 6 days. The goal of the digital twin is to give an estimated value for the expected storability (where the order of magnitude is important, for example, 1 day versus 5 days versus 2 weeks) to be able to keep track of the quality of different crops inside the room and minimise losses. When multiple crops are stored, the digital twin helps to indicate which products should be taken out soon (TTPU of around 1 day), or which can be stored for a longer time still (TTPU of multiple days or even weeks).

ii) The initial quality of the produce when it is brought to the room plays an important role in determining the TTPU accurately. For example, if a crop had to travel unrefrigerated for 4 days before reaching the cold storage room, the quality when arriving at the room will be drastically lower than the freshly harvested crop, leading to a decreased storability (lower TTPU). When a crop is checked-in into Coldtivate, the operator is prompted to ask the cooling user about when the crop was harvested (today, yesterday, 2 or more days ago). These answers map to a crop-specific quality value which is calculated assuming the crates have been stored unrefrigerated between harvest and check-in, and that is used as the initial TTPU. To be able to predict the quality at check-in as accurately as possible, it is important to answer this question honestly.

Within the calculation, it is assumed that the crop was kept at a constant temperature of 30 °C when travelling from the farm to the room. Probably, the temperature was variable throughout the day (e.g. lower during the night), which would influence the quality at check-in (e.g. the quality decreased less compared to storing continuously at 30 °C). If the crop was harvested, for example, 1.5 days ago, it would be appropriate to indicate '1 day ago' in the question at check-in in the app. In future versions of the app, the calculation can be refined to account for day and night temperatures based on the geo-location of the farm and cold storage room.

iii) The digital twin uses temperature sensor data to calculate the remaining quality during storage. To incorporate temperature variations in the room (e.g. room temperatures higher than the optimal temperature of the product, temperature peaks during door openings, etc) the model regularly recomputes the remaining quality of each crate.

To improve the model accuracy, it is important that the sensors are properly installed inside the room, so that the temperature measurements are representing the temperature the crops are experiencing. Hence it is crucial to make sure that the sensors are not accidentally taken out of the room, and that the sensors are functioning properly at all times and are able to send data to the cloud storage.







iv) The TTPU can be seen as a prediction in the future about 'how long can the product still be stored inside the cold storage room'. As we do not know what the room temperature in the future will be, we use the set temperature within the room to calculate the TTPU, assuming that in the upcoming days, the temperature within the room will equal the set temperature. Coldtivate is being refined to calculate the set temperature as follows:

- a) If the room is equipped with sensors connected to the Coldtivate app, the default setting is that the average temperature of the past 6 hours is taken as the set temperature.
- b) If the room sensors contain the set temperature as part of the API response, that value is used as a set temperature in the TTPU model.
- c) If no sensor data is available for the room, Coldtivate uses the last manual temperature as the set temperature.

The rate of quality loss and hence the storability are highly dependent on temperature. When the temperature increases, the expected storability also decreases. To make sure the displayed TTPU is as accurate as possible, the model is recomputed multiple times per day using the latest available temperature traces.

v) The digital twin currently assumes that the crops are harvested fully ripe. However, some crops, such as banana and tomato, might be harvested unripe (in a green stage). The ripening model is currently not yet implemented in Coldtivate. As a result, when green bananas or green tomatoes are brought to the room, the TTPU prediction will be less accurate (i.e. the TTPU will be too low).

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