Precooling and Cold Storage for Fruits and Vegetables

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Cold chain systems, such as cold storages, are crucial to minimizing postharvest losses of fresh fruits and vegetables. Cold storage alone cannot prevent crop losses, but should be considered as one component that needs to be integrated into a cold chain network from the point of harvest to the point of purchase by the consumer. Cold chains are still in their infancy in developing countries due to the lack of basic infrastructure and management skills needed to support the development of integrated cold chain systems.

Keywords: cold chain ; fruits and vegetables ; postharvest loss ; food and nutrition security

1. Cooling and Cold Storage of Fresh Fruits and Vegetables

A cold chain for perishable foods can be defined as the uninterrupted handling of the product within a low-temperature surrounding during the postharvest steps of the value chain [1]. After harvest, a food cold chain pathway includes precooling, bulk storage, distribution, retail cooling and household refrigeration before consumption. Although a cold chain does not necessarily have to include all of the aforementioned steps, it must involve at least one of these steps [1]. This section provides an overview of precooling and bulk storage methods for fresh fruits and vegetables.

Bulk cold storage refers to the storage of (large) quantities of produce after production and initial post-production handling. Bulk cooling may take place on farms, at production facilities, at collection/grading centers or at processing facilities. Precooling of products prior to bulk cooling is necessary in order to achieve desired temperature reductions faster than direct integration into bulk storage [2]. Cooling and cold storage require enough starting capital and running costs and reliable electricity supply. These preconditions are often not available to farmers in developing countries. Hence, small-scale farmers have no access to unbroken cold chains and the use of sustainable cold storage facilities [3].

In general, improving cold storage in food value chains provides significant development benefits, such as expanding access to suitable infrastructures and strengthening local management capacities. It also offers environmental protection by reducing waste and carbon emissions, providing efficient use of natural resources and accelerating economic growth through energy and cost savings and increased incomes to rural farmers [2][3][4].

1.1. Precooling Methods for Fruits and Vegetables

Elansari [5] defined precooling as "the removal of field heat from freshly harvested perishable produce in order to slow down metabolism and lower deterioration prior to transport or storage". Field heat means the difference in temperature between the temperature of harvested produce and the optimal storage temperature of that produce. In addition, field heat should be removed as fast as possible since, for most fresh produce, an hour's delay at field temperature conditions of 35 °C will lower shelf life to about a day even at optimal storage conditions [6]. Soon after harvest, fresh produce looses more water (through transpiration and respiration), probably due to stress at harvest. Additionally, water loss results in decreased product weight and freshness, while in extreme cases all of the produce becomes unsaleable. Therefore, rapid cooling of fresh produce soon after harvest reduces the rates of respiration and transpiration, ethylene production and microbial growth thereby enhancing its freshness and nutritional value and preventing or delaying chilling injury [5][7]. Furthermore, precooling increases the daily intake of produce into a cold storage facility, which should be less than 10% of its cooling capacity if produce is not precooled, reducing the thermal load of cold storage, since optimum storage temperature is reached more quickly [6]. Studies have shown that the postharvest losses of commercial fruits and vegetables are about 25–30% without precooling and only 5–10% with precooling [8].

The choice of a particular precooling method for fruits and vegetables depends on multiple factors, such as the characteristics of the produce (including chilling sensitivity, geometry and thermal properties), the amount of produce to be cooled, air temperature, airflow rate, relative humidity, packing configuration and stacking arrangement of the produce, energy efficiency of the method, the availability of skilled labor and the economic viability (capital and running costs) of the precooling method [5][6][9][10].

Several studies in the literature on precooling methods for fresh fruits and vegetables are available [5][7][9][11][12]. Precooling methods, such as refrigerated room cooling, passive evaporative cooling, forced-air cooling, water cooling and ice cooling, along with their impacts, are compared in **Table 1**.

Table 1. Comparison of precooling methods and their effects on horticultural produce [5][9].

Methods	Passive Evaporative Room Cooling (Use of Water-Soaked Media)	Refrigerated Room Cooling (Cold Air Is Circulated around Containers)	Forced-Air Cooling (Cold Air Is Forced through Containers)	Water Cooling (Cold Water Is Used for Fast Cooling)	Ice Cooling
Example of available systems	Clay-in-clay passively cooled rooms; zero-energy cooling chambers (sand and bricks); charcoal-filled walls of non-refrigerated rooms	Traditional cold rooms (pre-fabricated/self-built); retrofitted refrigerated container trailers; USDA Porta-cooler (small trailer-mounted pre-cooler)	Portable forced-air pre-cooler; Cool & Ship (insulated precooling box with A/C unit); TORNADO mobile forced pre-cooler	Mobile coolers; immersion-type conveyor coolers; shower-type batch coolers	Package ice—crushed or slurry ice
Typical cooling time (h)	40–100	20–100	1–10	0.1–1.0	0.1–0.3
Produce moisture loss (%)	No data	0.1–2.0	0.1–2.0	0–0.5	No data
Water contact with produce	No	No	No	Yes	Yes
Potential for decay contamination	Low	Low	Low	High	Low
Capital cost	Low	Low to medium	Low	Low	High
Energy efficiency	High	Low	Low	High	Low
Limitations and concerns	Applicability and effectiveness limited by climatic factors; severely restricted temperature range	Produce should not be harvested while hot to reduce water loss and/or microbial infections	Effectiveness is limited by air flow configuration used, which may increase cost	Recirculated water must be clean to avoid buildup of decay organisms	Ice melting causes physical hazards during operations; need for moisture-proof packages

1.2. Bulk Cooling Systems for Storage of Fruits and Vegetables

Common cooling methods for bulk storage are vapor-compression systems, sorption systems and evaporative cooling systems. These systems are compared in **Table 2**. The technologies differ significantly with regard to a range of characteristics, such as temperature and relative humidity range, as well as energy and refrigerant use. The choice of cold storage system to be installed and site selection depends on many factors that include [2][13]: the level of temperature and relative humidity required; the location chosen should be easily accessible and close to produce collection points; uninterrupted supplies of electricity and water the availability of capital and skilled labor; and the economic value generated through cold storage to justify investment and running costs. Moreover, the selected technology needs to be sustainable and environmentally friendly, with zero or low greenhouse gas emissions [4]. Where feasible, the use of off-grid electricity, zero or renewable energy, and natural refrigerants should be highly encouraged. Accordingly, solar photovoltaic systems, wind power and biomass energy are gaining traction in the fast-growing renewable energy sector in Africa [14]. For instance, with 69% of the total final energy consumption in 2017 being from renewable energy sources, Sub-Saharan Africa showed the highest share of this sector. Hence, sustainable energy can be effectively harnessed to power off-grid cold storage facilities.

Table 2. Comparison of cold storage methods and designs with key operational characteristics [2].

Methods	Common Systems (*Design*)	Energy Requirement	Temperature Provided	Refrigerant
	Zero-Energy Cooling Chamber (*Walk-in cold room/chest-type cooler*)	**No energy input required; optional use of low-voltage electric pumps and fans**		
Evaporative coolers	**USDA-Portacooler Evaporative Forced-Air (*Refrigerated trailer*)**	**12/24V DC deep cycle battery**	**Vary widely depending on outside temperature and humidity; no less than approx. 15 °C**	**Water (frequent refills required)**
	Charcoal cooler (*Walk-in cold room/chest-type cooler*)	**No energy input required; use of electric pumps/fans is optional**		
Sorption coolers	**Cooler (*Solar adsorption cooling*)**	**Thermal energy 520 kWh/a/~60 W (80 °C)**	**4 °C to 8 °C**	**Distilled water**
	Solar Polar (*Adsorption cooling modules*)	**Solar thermal energy (evacuated tube); thermal energy storage**	**Not specified**	**Ammonia–water**
	DanSolar Cold Storage Chamber (*Walk-in cold room*)	**Off-grid standalone solar PV refrigeration**	**−10 °C to 10 °C**	**Not specified**
Vapor compression coolers	**Steca PF 166/PF 240 (*Chest-type cooler*)**	**12/24 V DC designed for off-grid solar PV operation**	**2 to 12 °C (refrigerator) or −20 to −10 °C (freezer)**	**Halogenated (R134a)**
	CoolBot (*Walk-in cold room/refrigerated trailer)*	**110 V AC**	**2 °C and above**	**Halogenated or natural refrigerant**

1.2.1. Vapor-Compression Cooling System

Vapor-compression cooling is an electric-driven system which relies on phase changes of refrigerant fluid [2][15]. During operation, a circulating liquid refrigerant (halogenated or natural refrigerants) is exposed to different pressures successively. When subjected to low pressure surroundings, the liquid refrigerant evaporates while it absorbs and removes heat from its surroundings to provide a cooling effect. Subsequently, the gaseous refrigerant is first compressed and then condensed returning to its liquid state, while rejecting the heat previously absorbed to the environment.

This cooling method provides a full temperature range and a relative humidity of 80% to 90% which makes it suitable for chilling even high-value produce. Economically, this kind of cooling system has lower initial investment costs but may have high running costs depending on whether the cold room is pre-fabricated or owner built, new or used, and high maintenance costs [9]. This system has a comparatively high Coefficient of Performance (COP), which is the ratio between refrigerating capacity and power consumed. A shortcoming of this method has been the use of halogenated refrigerants, which, though widely available and relatively cheap, are not environmentally friendly. Natural alternatives, such as hydrocarbons, carbon dioxide and anhydrous ammonia, are now commercially available as alternatives but they are still relatively expensive in developing countries [2].

1.2.2. Sorption Cooling System

A sorption cooling system runs on thermal energy and relies on physicochemical attraction between a natural refrigerant and an adsorbent or absorbent [2]. Ammonia–water or lithium bromide–water combinations are mostly used in absorption systems, while silica gel–water or zeolite–water working pairs are mostly used in adsorption systems. To create a cooling effect, the refrigerant is subjected to a low-pressure surrounding in order to evaporate at ambient temperature while absorbing heat from its surrounding. Subsequently, the gaseous refrigerant is absorbed or adsorbed by the absorbent or adsorbent material. As a result, the pressure in the evaporator is reduced allowing more refrigerant to evaporate. Thermal energy is then used to evaporate the refrigerant from the adsorbent or absorbent and restore the original conditions.

Similar to vapor-compression systems, sorption cooling can provide a full temperature range and low/medium relative humidity. This makes it suitable for chilling sensitive and even high-value produce. Sorption cooling systems require higher capital costs and very low operating costs due to their flexible use of low-grade thermal energy sources (such as solar and industrial waste heat) and low maintenance requirements. In addition, sorption systems have lower COP compared to vapor-compression systems [2].

1.2.3. Evaporative Cooling System

An evaporative cooling system utilizes the cooling effect resulting from the evaporation of water [2][16]. Water is applied to a porous surface (e.g., sand or charcoal). As temperatures increase, it begins to evaporate. As water undergoes a phase change from liquid to gas, it absorbs energy in the form of heat from the surrounding air, thus cooling it. This simple cooling method only requires water as a coolant, running freely over a porous surface, and, since the process is driven by heat from the surrounding environment, requires no additional energy [13]. However, the cooling process if it relies on natural flow of air is slow and can be speeded up by using fan-assisted air flow systems.

Evaporative cooling systems are comparatively cheap due to the fact that they require very little or no energy input, can be constructed using locally available materials (e.g., bricks, charcoal and sand) and water as a coolant, and thus can be suitable for low-value produce [9][13][16][17]. However, this method provides limited temperature control due to its inherent dependence on local climatic conditions [18]. In most cases, temperatures above 15 °C and very high relative humidity are achieved. Hence, evaporative systems are mostly suitable for non-chilling fruit and vegetables, especially tropical/sub-tropical crops, such as tomatoes, mangoes, bananas, sapotas, plums, grapes, capsicums, cluster beans, peas, radishes, peaches, carrots, cucumbers, beats, ladies fingers, green peppers, cauliflowers and leafy vegetables [13]. As the availability of water is a critical factor in the operation of evaporative cooling systems, a continuous supply of reasonably sanitized and soft (i.e., no or low levels of calcium or magnesium) water in sufficient quantity, along with suitable water pumping technology and water storage reservoirs, are required [2].

2. Cold Storage Management

Prior to precooling and bulk storage of fruit and vegetables, appropriate harvesting and handling of fresh produce, taking into account maturity and ripeness levels and proper harvesting time (during periods of low temperatures or sunlight intensities), along with sorting and grading and adequate packaging, should be considered to avoid loss of quality through mechanical, chilling and freezing injuries and microbial growth, to extend shelf life during cold storage [7][11][12][13][19][20].

To improve the shelf life and quality of fresh fruits and vegetables, cold storage should be managed properly with regard to temperature, relative humidity levels, air flow, space between storage containers, mixing of compatible produce (e.g., according to temperature demand, odor production and ethylene sensitivity), as well as the management of product in-and outflow, which should follow the 'First In, First Out' principle [6][11][20][21]. In fact, the principle is to store each crop separately and the climacteric products at similar maturity stages. Since this is not always feasible, compatible crops can be stored together. For instance, with respect to odor transfers, apples and pears should be separated from celery, cabbage, carrots and onions. Additionally, storing celery with onions or carrots and citrus fruits with strongly scented vegetables should be avoided. Ethylene-producing crops, such as bananas, apples, avocadoes, peaches, plums and tomatoes, should be stored separately from ethylene-sensitive crops, such as carrots, lettuce, cucumbers and potatoes. Further to this, cold storage facilities should be cooled to the storage temperature required for the specific products before produce is stored.

Cold storages could be accompanied by modified-atmosphere technologies, such as Controlled Atmosphere (CA) storage and Modified Atmosphere Packaging (MAP), to further improve the effect of cooling on fresh fruits and vegetables. While CA storage replaces the traditional refrigerated storage rooms, MAP focuses on the environments of products within packaging. Nevertheless, both technologies consider the manipulation of the level of gases, such as oxygen (O_2), carbon dioxide (CO_2) and nitrogen (N_2), as a means to control fresh produce quality and storability through suppression of respiration (via high CO_2 and low O_2 conditions), inhibition of ethylene action (via high CO_2, low O_2), inhibition of decay (via high CO_2) and inhibition of browning for fresh-cut produce (via low O_2) [22][23]. In addition, the amount of water loss of fresh produce is reduced considerably, particularly in MAP. The application of CA storage is more intensive and active, as it relies on costly techniques, including the use of CO_2 scrubbing methods to control CO_2 levels, improved technologies for generating low O_2 atmospheres and improved sense-and-respond systems for atmosphere control. On the other hand, MAP is more passive and hence cost-effective in low-income SSA countries. MAP can be further improved through the use of biodegradable plastics, sensors and the incorporation of bioactive compounds, such as absorbers of CO_2, O_2 and water vapor.

Edible coatings, such as some lipids, proteins, polysaccharides or mixed biopolymers, could be applied on fresh fruits and vegetables during cold storage to maintain quality (including texture, color and nutritional value) and extend shelf life [24][25]. Edible films form a thin semi-permeable layer when applied over the surface of fresh produce to provide a modified atmosphere during storage. As a result, gas transfer, water loss, color change and aroma loss are reduced. In addition, some edible films are carriers of antimicrobial and antioxidant agents and hence help to control microbial growth and biochemical activities, such as respiration and transpiration. Therefore, where applicable, the combination of optimal storage temperatures, relative humidity levels, atmospheric gases and edible coatings could improve the effectiveness of cooling techniques for fresh produce.

The operation and maintenance of a cold storage facilities is necessary to ensure that the purpose of cooling is achieved. Due to the costly and energy-intensive nature of cold storage facilities [2], the door to the cold storage room should be opened as few times as possible, particularly in the early morning or evening hours. In addition, the usage of lighting and fans should be kept to a minimum [7]. A logbook should be used to keep all information on incoming produce up-to-date, such as harvest date, precooling method used, arrival and storage time, quality, quantity, storage conditions, energy consumption, and location within the cold storage facility [6]. Moreover, good hygienic practices inside the cold storage facility, such as personnel hygiene, facility cleanliness, maintained with hypochlorite solution and ozone generators, and regular ventilation to reduce concentrations of carbon dioxide, ethylene and odors, should be taken into consideration [26].

Cold storage control systems can also be integrated with modern intelligent control methods, such as frequency-controlled compression technology, Programmable Logic Controller (PLC) technology, fuzzy control, in combination with Internet of Things, to optimize the control of cold storage for low-energy consumption, cost saving and low environmental impact [27].

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