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INNOVATIVE PRECOOLING TECHNIQUES TO PRESERVE THE QUALITY OF FRUITS AND VEGETABLES

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Abstract

Precooling is critical in post-harvest management to extend the shelf life and maintain the quality of fruits and vegetables. This article explores novel precooling techniques and their effects on produce quality, starting with an overview of the significance of fruits and vegetables to human health. Various methods, including forced-air cooling, hydrocooling, vacuum cooling, ice cooling, cryogenic cooling, and evaporative cooling, rapidly reduce produce temperatures to slow physiological and biochemical processes. These techniques are selected based on produce characteristics and desired cooling rates. Advances focus on optimizing cooling uniformity, integrating eco-friendly refrigerants, and enhancing energy efficiency. Future research aims to understand the cellular impacts of precooling and develop innovative, sustainable methods to improve the quality and longevity of fresh produce.

Keywords: Precooling, fruits, vegetables, techniques, novel methods

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Introduction

During the post-harvest supply chain for fruits and vegetables, the losses can range from 13% to 38% before reaching consumers. The fruit and vegetable industries encounter numerous challenges, including moisture loss, texture changes, spoilage, color changes, and pigment loss. To mitigate these issues, precooling is implemented to remove field heat from fresh produce. Precooling is crucial in the handling and storage of produce as it involves rapidly lowering the temperature to slow down physiological and biochemical processes, thus extending shelf life. Conventionally, various precooling methods were used, such as room cooling, hydrocooling, using wet cloths, and earth pits. However, advancements in technology have led to the development of more efficient methods, including forced-air cooling, hydro-cooling, ice cooling, vacuum cooling, cryogenic cooling, and evaporative cooling. Despite their technical differences, all these techniques aim to transfer heat from the produce to a cooling medium like air or water. The choice of the most suitable technique depends on factors such as the commodity's characteristics, container type, desired cooling rate, and the conditions for storage and shipping (Duan et al 2020).

The effectiveness of these innovative precooling techniques is influenced by the product's characteristics—size, shape, and composition—as well as the cooling rate. Factors such as the initial temperature of the produce, the rate at which the cooling medium surrounds it, and the temperature differential between the produce and the cooling medium play critical roles. Different precooling methods operate under varied conditions, affecting the final quality of the produce in distinct ways. Understanding how these techniques impact the quality of fresh fruits and vegetables is essential for enhancing product quality, which is crucial for consumer health and market preference (Senthilkumar et al 2015). This article will explore novel precooling techniques and their effects on produce quality, beginning with an overview of the significance of fruits and vegetables to human health.

Importance of Precooling

Precooling involves rapidly reducing the temperature of freshly harvested produce to the optimal storage temperature, typically around 2-6°C for most fruits and vegetables. Here are some reasons why precooling is important:

1. **Preservation of Quality:** Precooling helps to preserve the quality and freshness of fruits and vegetables by slowing down the metabolic processes that lead to deterioration. Rapid cooling minimizes water loss, reduces decay, and maintains texture, flavour, and nutritional value.
2. **Extended Shelf Life:** By quickly lowering the temperature, precooling extends the shelf life of perishable fruits and vegetables. This is crucial for maintaining product quality during storage, transportation, and retail display.
3. **Minimization of Post-Harvest Losses:** Proper precooling significantly reduces post-harvest losses due to spoilage. It helps to prevent wilting, softening, and other forms of deterioration that can occur if produce is left at higher temperatures for too long after harvest.
4. **Marketability:** Consumers prefer fresh-looking and fresh-tasting fruits and vegetables. Precooling ensures that produce arrives at market with a better appearance and taste, which can enhance marketability and consumer satisfaction.
5. **Food Safety:** Precooling can also contribute to food safety by quickly lowering the temperature of produce, which helps to slow the growth of pathogenic bacteria and reduce the risk of foodborne illness.
6. **Compliance with Regulations:** In many countries, precooling is a required step in the post-harvest handling process to comply with food safety regulations and quality standards. It is often a critical control point in ensuring that produce meets regulatory requirements.
7. **Optimal Transport Conditions:** Precooled fruits and vegetables are better able to withstand the rigors of transportation, especially over long distances or in hot climates. This helps to maintain quality from farm to market.
8. **Uniform Cooling:** Precooling ensures that all parts of the produce are uniformly cooled. This helps to prevent uneven ripening, which can occur if fruits and vegetables are not cooled quickly and uniformly.

9. **Compatibility with Packaging:** Precooling facilitates the packaging of fruits and vegetables by reducing their temperature, which can prevent condensation inside packaging materials that could lead to moisture-related issues and microbial growth.
10. **Facilitates Cold Chain Management:** Precooling is an integral part of maintaining the cold chain, which is the uninterrupted series of refrigerated production, storage and distribution activities. It ensures that produce remains at optimal temperatures throughout its journey from farm to consumer, reducing the risk of spoilage and maintaining quality.

Methods of Precooling:

Various methods used to remove field heat from the fresh produce are explained below:

Room Cooling

Room cooling lowers the temperature to 20-22°C, making it suitable for moisture-sensitive produce. This method involves placing produce in containers—like wooden, fiberboard, or plastic boxes—within a cold room where cold air circulates. Due to its slow cooling rate, room cooling is best for small quantities or less perishable produce. In a typical room cooling system, cold air is introduced near the ceiling and circulates around the containers before being re-cooled by heat exchangers. Forced or induced draft coolers with finned evaporator coils and fans provide the cooled air. Effective cooling requires well-ventilated packaging and proper stacking, with air velocities of at least 60 m/min to ensure adequate turbulence for heat removal. However, since room cooling relies on conduction, it results in slow and uneven temperature reduction, making it suitable only for produce that can handle gradual cooling. For highly perishable fruits, the room should achieve an airflow rate of 170 to 225 m³/min for a 15,000 kg capacity, cooling produce to 5°C within about 12 hours. Proper spacing between containers and high relative humidity (90-95%) are crucial to prevent drying. Room cooling is less effective for bulk bins due to their larger mass, which requires more intensive cooling. This method is best for produce like beets, cabbage, potatoes, pumpkins, apples, pears, and peaches, although faster precooling methods may be more advantageous for these items (Brosnan et al 2001).

Figure 1. Various types of Precooling

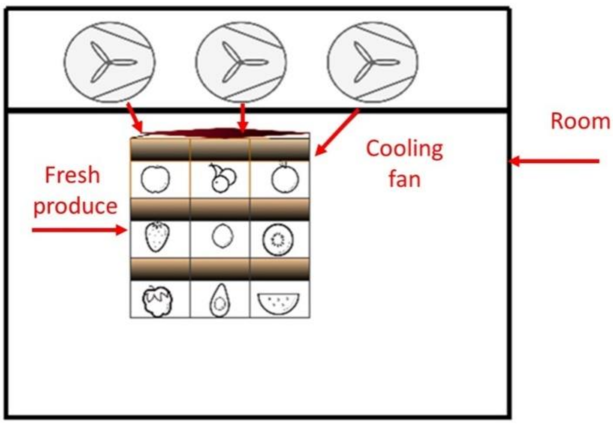

Figure 2. Room cooling

Hydrocooling

Hydrocooling uses chilled water to rapidly lower the temperature of bulk produce or items in smaller containers before packaging. This process can involve flooding, spraying, or immersing produce in cold water, with various hydrocooler designs offering different cooling efficiencies. The main types of hydrocoolers include:

1. Conventional (Flood) Type: Floods packaged produce as it moves through a cooling tunnel.
2. Immersion Type: Submerges loose produce in cold water, then transfers it via a conveyor with an overhead shower.
3. Batch Type: Sprays chilled water over produce for a set time, though it often results in uneven cooling, creating 'hot spots.'

Immersion and flood types are more efficient due to better surface coverage and flexibility in packaging, making them suitable for various produce. Hydrocooling is particularly effective for produce that can withstand wetting and is commonly used in market preparation. However, it poses a risk of contamination from decay-causing organisms in recirculated water. To prevent this, mild disinfectants like chlorine or approved phenolic compounds are used, provided they do not negatively affect the produce. A key advantage of hydrocooling is its rapid temperature reduction, which takes 20-30 minutes compared to several hours with forced air cooling. Hydro-air cooling, a specialized variant, uses refrigerated air and fine mist to enhance sanitation and reduce water use, with its effectiveness depending on the air-water ratio (Brosnan et al 2001).

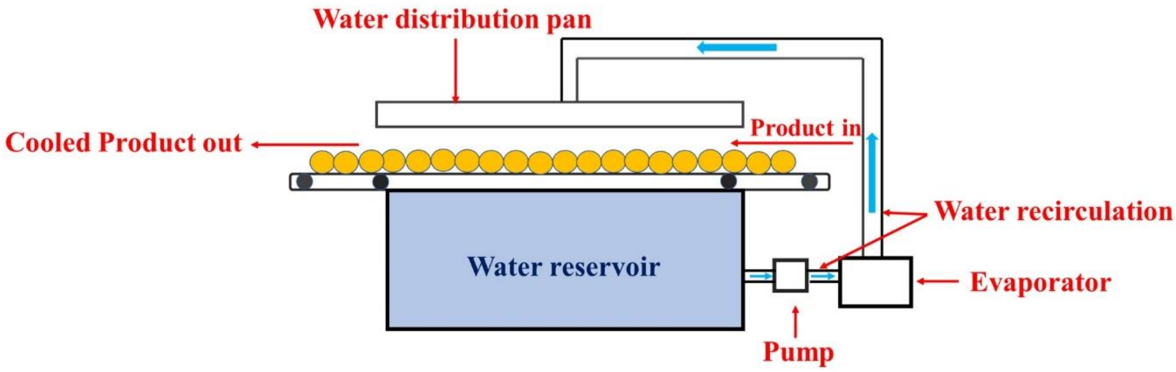

Figure 3. Hydrocooling

Vacuum Cooling

Vacuum cooling is an efficient technique for rapidly reducing the temperature of horticultural produce by leveraging the evaporation of moisture. This method operates by lowering the pressure in a vacuum chamber, which in turn lowers the boiling point of water and facilitates effective cooling. The core principles of vacuum cooling are:

a. At atmospheric pressure (1013 mbar), water boils at 100°C. As pressure decreases, the boiling point of water also drops. For example, water boils at 20°C at 23.37 mbar and at 0°C at 6.09 mbar.
b. The latent heat required for water to evaporate is extracted from the produce, reducing its sensible heat and cooling it.
c. Efficient removal of water vapor from the produce is essential to sustain the cooling process, typically achieved using a condenser within the chamber.

During the vacuum cooling process, the chamber pressure is initially reduced to approximately 20 mbar, causing minimal evaporation while the produce temperature remains stable until it reaches the "flash point." At this point, the produce rapidly loses moisture and cools. For instance, if the initial temperature of the produce is 20°C, the flash point may occur around 24 mbar. As water vapor replaces the evacuated air, it must be swiftly removed to prevent prolonging the cooling cycle. The pressure is further reduced until the desired final temperature is achieved, but pressures below 6.09 mbar are generally avoided to prevent excessive energy use and the risk of freezing. Several factors influence cooling efficiency, including the surface area-to-mass ratio of the produce, the ease with which water is released from the tissues, and the rate at which the vacuum is applied. Produce with a high surface-to-volume ratio and those that release moisture readily cool more effectively. To prevent surface freezing before reaching the target temperature, a "bouncing" procedure may be used, intermittently turning the vacuum pump off and on to maintain a temperature above freezing. One notable drawback of vacuum cooling is moisture loss, leading to a weight reduction of approximately 5 to 5.5% for every 1°C decrease in temperature. Despite this, vacuum cooling offers rapid and uniform cooling, making it a preferred technique for many products, particularly those without hermetically sealed packages that allow for free evaporation (Makule et al 2022).

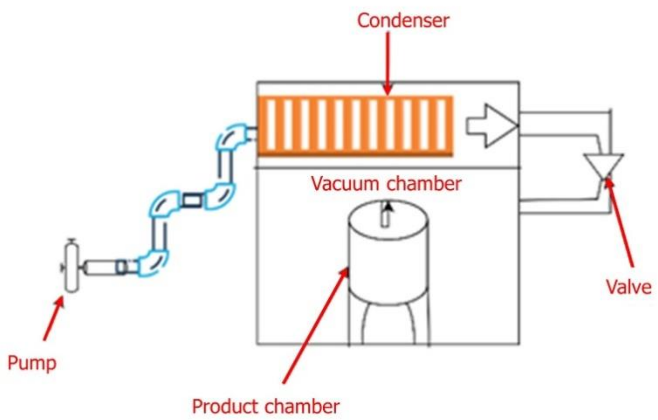

Figure 4. Vaccum Cooling

Ice Cooling

Ice cooling employs a mixture of ice and water to form a slurry that directly contacts and cools produce inside its packaging. This technique is particularly useful for precooling temperature- and humidity-sensitive fruits and vegetables. Before more advanced methods emerged, contact or package icing was the primary cooling technique, where slush, flaked, or crushed ice was placed over produce in shipping containers. This method, while effective, often resulted in uneven cooling as the ice stayed in place until it melted. Liquid icing, a more advanced approach, uses ice slurry and combines aspects of package icing and hydrocooling. It involves pumping a mixture of finely crushed ice and water into open containers on a conveyor or injecting it through vents in pre-packed produce. This method ensures more uniform cooling and prevents produce from drying out. Although ice cooling requires significant ice and waterproof containers, increasing costs, it can maintain low temperatures during short-distance transport, potentially eliminating the need for refrigerated transport. Despite its advantages, icing can wet produce, creating conditions for post-harvest diseases and soft rots, and the melting ice may leave packages partially filled. Nonetheless, ice cooling is generally quicker than hydrocooling and demands careful water quality and sanitation (Makule et al 2022).

Forced Air Cooling

Forced air cooling, also known as pressure cooling, was developed to rapidly eliminate field heat immediately post-harvest. This method enhances traditional room cooling by subjecting produce packages to a differential air pressure, where one side experiences higher pressure than the other. Precise stacking arrangements and baffles are essential to direct cooling air through the containers rather than around them. For effective forced air cooling, it is crucial to align the container's vent openings with the airflow direction and minimize obstructions from packaging materials that could impede air circulation (Figure 5). The modest pressure differential between the two sides of the containers facilitates efficient air movement and heat transfer, expediting the cooling process. Forced air cooling can be implemented in several configurations:

1. High-velocity air circulation within refrigerated rooms.
2. Airflow through the voids of bulk products on continuous conveyors within cooling tunnels.
3. Pressure differential techniques to promote airflow through packed produce.

The velocity of the cold air is the primary variable affecting the cooling rate, with the fixed attributes of the produce, such as size and thermal properties, being secondary. Additionally, the cold air temperature must be maintained above a threshold to avoid chilling injury. Typically, cool air for forced air cooling is produced by:

a. Direct expansion refrigeration systems
b. Ice bank cooling systems
c. Water cascade systems

Forced air coolers use either centrifugal (squirrel cage) or axial fans to circulate the cold air. The choice of fan depends on the required airflow and static pressure, influenced by the type and quantity of produce, its arrangement (bulk, boxes, or stacking), and the desired cooling rate. Differential pressures generally range from 0.6 to 7.5 mbar, with airflow rates between 0.001 and 0.003 m³/s per kilogram of product. Produce types that can be effectively cooled using this method include apples, apricots, avocados, various beans, bell peppers, blueberries, boysenberries, cabbage, carrots, cauliflower, figs, and cucumbers (Albayati et al 2007).

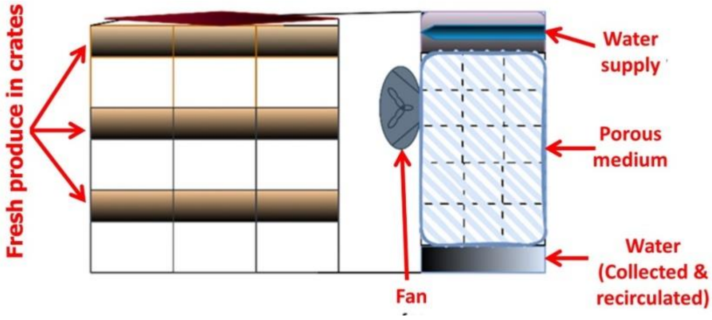

Figure 5. Forced Air Cooling

Cryogenic Cooling

Cryogenic cooling utilizes the latent heat of vaporization of liquid nitrogen or the sublimation of solid CO_2 (dry ice) to achieve extremely low temperatures—up to -196°C with liquid nitrogen and -78°C with dry ice. In this process, produce is conveyed through a tunnel where the liquid nitrogen or dry ice evaporates, cooling the produce rapidly. However, the extreme temperatures involved present a risk of freezing, which can negatively impact the quality of the produce as a fresh market commodity. To mitigate this risk, precise control of the evaporation rate and conveyor speed is essential. While cryogenic cooling systems have relatively low initial installation costs, they incur high operational expenses. This method is particularly advantageous for crops with limited seasonal production periods, such as soft fruits, as it allows growers to avoid the substantial capital investment required for other cooling technologies. Despite the high costs associated with liquid nitrogen, dry ice, and other non-toxic refrigerants, cryogenic cooling is cost-effective for high-value products due to its efficiency in short-term applications. As a result, growers can circumvent the significant capital expenditures typically associated with alternative cooling methods by using cryogenic cooling for their operations (Alabi et al 2021).

Evaporative Cooling

Evaporative cooling is a cost-effective technique for reducing produce temperatures, especially in low-humidity environments. This method involves drawing dry air through moist materials or a fine mist, and then through containers of produce. Water is applied to a porous medium, such as sand or charcoal. As the temperature rises, water evaporates, absorbing heat from the surrounding air during the phase transition from liquid to gas, which results in cooling. This system relies solely on water as a coolant and operates without additional energy inputs, utilizing ambient heat. However, when relying solely on natural airflow, the cooling rate can be slow. Efficiency can be improved with fan-assisted air circulation systems. Evaporative cooling systems are relatively inexpensive due to their minimal energy requirements and the use of locally available materials, such as bricks, charcoal, and sand. This makes them suitable for low-value produce. Despite their affordability, evaporative cooling offers limited temperature control as it depends on local climatic conditions. Typically, these systems can achieve temperatures above 15°C with high relative humidity, making them ideal for non-chilling fruits and vegetables, particularly those grown in tropical and subtropical regions. Examples include tomatoes, mangoes, bananas, sapotas, plums, grapes, bell peppers, cluster beans, peas, radishes, peaches, carrots, cucumbers, beets, okra, green peppers, cauliflower, and leafy greens. The effectiveness of evaporative cooling systems is highly dependent on a continuous supply of adequately sanitized and soft water (low in calcium or magnesium), along with appropriate water pumping technology and storage facilities (Alabi et al 2021).

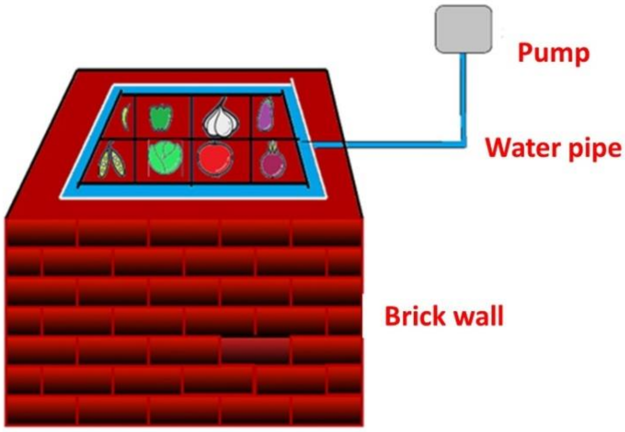

Figure 6. Evaporative Cooling

Future Scope

The future of precooling in postharvest management holds significant promise for enhancing the quality and longevity of fruits and vegetables. Research into cellular and molecular impacts of various treatments is critical to optimize protocols and explore novel timing and temperature combinations. Understanding species-specific responses and pre-harvest factors areessential for targeted strategies. Optimizing packaging and stacking patterns to enhance cooling rates and uniformity is another vital area. Computational Fluid Dynamics (CFD) offers a cost-effective design alternative, with advanced turbulence modelling providing greater accuracy. Integrating eco-friendly refrigerants, renewable energy sources, and innovative technologies will enhance energy efficiency and sustainability in post-harvest practices.

Conclusion

Implementing precooling techniques in post-harvest management is crucial for mitigating food waste by maintaining quality and prolonging shelf life, while also reducing cooling demands throughout the cold chain. Common methods, such as forced air cooling, vacuum cooling, hydrocooling, and room cooling, must be matched to specific produce characteristics. Alternative methods like progressive, delayed, and rapid cooling also exist. Evaluating precooling effectiveness involves assessing cooling rate and homogeneity. Further research is needed to enhance precooling uniformity and speed while minimizing energy use. Exploring cellular and molecular impacts, along with modelling, engineering, physiological, and commercial factors, is essential for optimizing precooling techniques.

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