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POST-HARVEST TECHNOLOGIES AND COLD CHAIN MANAGEMENT: A REVIEW

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ABSTRACT

Post-harvest technologies and cold chain management are essential components in preserving the quality, safety, and economic value of perishable goods throughout their supply chains. Post-harvest handling practices, including sorting, cleaning, packaging, and pre-cooling, minimize spoilage and maintain market readiness. The dry chain emphasizes moisture control to prevent microbial growth and quality degradation in non-perishable commodities like grains, while the cold chain employs temperature regulation to extend the shelf life of perishable products. Recent advancements in digital tools, such as the Internet of Things (IoT), blockchain, and artificial intelligence (AI), have enhanced real-time monitoring, traceability, and supply chain optimization. These innovations, alongside emerging technologies like digital twins and advanced sensors, hold promise for improving cold chain operations and integrating sustainable practices. Future possibilities include the development of energy-efficient refrigeration systems, expanded accessibility in developing regions, and the fusion of dry and cold chain methods to tackle global food security challenges. These advancements underscore the critical role of post-harvest and cold chain systems in reducing losses and ensuring efficient global distribution.

***Keywords*:** Post harvest, Dry chain, Cold chain, Harvesting losses, Nanotechnology

Introduction

Agriculture employs over two-thirds of the Indian population. India's horticulture production, comprising fruit and vegetable crops, was anticipated at 326.6 million metric tons in FY2020 (Manida, 2020). India is now the world's second greatest producer of fruits and vegetables. The country ranks first in output. Fruits such as banana, mango, citrus, papaya, guava, grapes, apple, pineapple, and sapota make up over 85% of total fruit output. India produces several fruits such as almonds, walnuts, jackfruit, bael, ber, custard apple, kiwi, passion fruit, peach, pear, plum, and strawberry. However, over 40% of total food items are lost each year. Fruits and vegetables, with short shelf life, account for 70% of food waste (Biswas, 2021; Chauhan, 2013). Over the past century, the production sector in high-income nations has used research-driven technical advancements to decrease post-harvest losses and increase the quality of perishable items (Kader, 2006). Technologies such as pre-cooling, refrigerated storage, drying, controlled atmosphere storage, improved packaging, regulated ripening, growth-regulating chemicals, and others ensure high-quality fruits and vegetables for consumers year-round and reduce postharvest losses during marketing. Low- and middle-income countries (LMICs) experience around 40% loss of harvested perishable items before consumption (Kader, 2005; Spang *et al.,* 2019). Tomatoes are the most popular horticultural goods, accounting for the majority of canned vegetables. In India, tomatoes generated around 218 billion Indian rupees (INR) to the economy in 2018 (Statistics, 2019). However, the most significant issue with tomato supply chain cultivation is shelf life, since ripened fruit must be stored at a temperature of 10-15 degrees Celsius (C) and relative humidity of 80-90% in the postharvest phases. As a result, the fruit must be transported with extra care in a refrigerated vehicle and packaged appropriately for factory delivery (Arun, 2017). In India, inadequate storage and transportation facilities result in the loss of 20-40% of tomatoes (Fernandes, 2017).

Cold chain management is crucial in today's perishable industries worldwide. According to (Singh *et al.,* 2018), the process of planning, implementing, and controlling the flow and storage of perishable goods, related services, and information enhances customer value while ensuring low costs. Cold chain logistics maintain all items fresh and sealed using thermal and refrigerated packaging. Thus, cold chain development is a critical component of food-related logistics progress and should be better integrated into agricultural and food-related objectives and action plans. Horticulture, meat, and dairy have risen in India's cold chain during the last decade (Narula, 2011), and they are predicted to increase by 13-15% in the next five years (Chakraborty, 2020).

Post Harvest Losses: Causes and Concerns

Fruit and vegetable losses after harvest can be up to 50% due to restricted shelf life and poor processing and marketing facilities. Inadequate pre-production and post-harvest management procedures increase losses, negatively impacting consumer pricing, farmer revenue, and nutritional value. Without sufficient farm storage or access to a packing plant, perishable food is generally sold directly after harvest without processing or wrapping. Solid waste from urban horticultural crops can clog drains, causing water blockages, pollution, and unhygienic conditions (APARI, 2010). Postharvest losses and waste in horticultural products are significant in both developed and developing nations, with varying degrees of reduction depending on the handling chain. Developing nations often experience higher losses during the post-harvest and handling stages owing to limited infrastructure and inefficient procedures. Increasing food production is a possible approach to meet the increased need for substance. Rather of focusing just on increasing output, it's important to prioritize effective food distribution and protect agricultural goods from loss during many stages, such as processing, retailing, fields, shipping, and storage.

Storehouse

Storage technology may enhance marketing efforts, increase value, and overcome quarantine limits. Additionally, they contribute significantly to the advancement and globalization of the horticulture sector. Effective temperature management is crucial for storage systems, as it is the fundamental technology. Cold storage can be enhanced with various storage strategies such as managing humidity, adjusting the atmosphere, correct packaging, and chemical treatments (Watkins *et al.,* 2004). Long-term storage needs proper facilities, cleanliness, and monitoring. Controlling cleanliness, temperature, and humidity is critical in closed structures such as granaries, warehouses, and hermetic bins. Pest and mold damage can deteriorate facilities and reduce food quality, value, and quantity. Temperature affects the metabolism of ethylene in numerous ways. Elevated ethylene generation during refrigerated storage may suggest harm to perishable products susceptible to cold temperatures (Cooper *et al.,* 1969). Insufficient drying and storage conditions are the primary causes of postharvest insect and fungus contamination in dried goods (Kumar and Kalita, 2017). Fungal infection in dried foods lowers their market value, makes them unpalatable, and can even be dangerous. Drying after harvest is a great technique to stabilize items and store them without refrigeration. To ensure success, the product must be dried and kept at a water activity (AW) of less than 0.65 (65% equilibrium relative humidity) (Bradford *et al.,* 2018).

Harvesting Losses

Harvest dates significantly impact the quality and shelf life of fruits and vegetables. Premature harvesting for financial reasons might result in immature food with poor quality and higher vulnerability to harm (Azabağaoğlu, 2018). However, mature fruits have a shorter shelf life. Overripe and under ripe fruits are more prone to create physiological problems. Early harvesting reduces crop quality and value. Unripe or overripe vegetables might cause batch losses (Kader, 1995). Harvesting practices may also cause losses (Liu, 2014). According to (Kader, 2013), high temperatures accelerate ripening and softening, as well as degradation and water loss. Low relative humidity can lead to increased water loss, and many packages used in LMICs cannot sustain high relative humidity levels.

Poor packing, shipping, and roads can cause physical damage, leading to increased water loss, ethylene production, accelerated ripening, and deterioration (Kader, 2010).

Transportation

Transportation expenses significantly affect consumer pricing, particularly in complicated distribution systems that service major cities and outlying areas. Transportation expenses might sometimes be higher than the cost of producing items (Condratchi, 2012). Such losses, particularly in less developed countries, have a substantial influence on global food security and economic sustainability. According to research, the Food and Agriculture Organization (FAO, 1959) reports that around 14% of the world's food is wasted during post-harvest phases, including transportation. Several variables influence transportation losses. Physical damage to produce is typically caused by poor packing or hard handling during loading and unloading. Perishable items such as fruits, vegetables and dairy products are particularly prone to deterioration owing to delays and a lack of temperature control during transit. Poor infrastructure, such as muddy roads, insufficient cars, and poor logistical systems, exacerbates the problems, particularly in rural areas. Furthermore, vast distances between farms and markets increase the danger of spoiling, especially when transportation systems lack sufficient refrigeration.

Mitigating these losses entails improving shipping and handling methods. Investing in cold chain logistics, such as refrigerated vans and insulated containers, may drastically minimize the spoiling of perishable commodities. Training staff in suitable handling practices, as well as strengthening infrastructure such as roads and rail networks, can also assist to reduce losses. Governments and stakeholders must work together to ensure farmers have access to efficient, cost-effective transportation solutions. Addressing transportation losses is critical to minimizing food waste, increasing farmer income, and boosting global food security. The agricultural supply chain may be enhanced by concentrating on new solutions and infrastructural upgrades, ensuring that food is transported safely and efficiently from farmers to consumers.

Improper Handling

Consumer preferences are influenced by their appraisal of available options for a product, whether it's a service or item (Kotler, 2008). Improper management of post-harvest produce is a major source of food loss and quality deterioration worldwide. This problem stems from a lack of proper procedures at important phases such as sorting, packing, shipping, and storage. Fresh fruits and vegetables account for around 50% of home food waste (FAO, 2011). According to a research (WRAP, 2008), fruits and vegetables account for 39% of all residential trash. Another research found a comparable amount of roughly 40% in residential waste. Consumers often waste money due to excessive spending, poor home storage, and lack of planning. Individual trash production is influenced by both material belongings and societal variables such as income, gender, lifestyle, and home storage choices (Porat *et al.,* 2018). The Food and Agriculture Organization (FAO) estimates that up to 30% of food is lost globally during post-harvest procedures, emphasizing the gravity of the situation. Poor handling procedures frequently cause physical harm to product, such as bruises, cuts, and crushing. These injuries not only diminish the marketability of the product, but also speed up deterioration by exposing it to microbial contamination and enzymatic activity (FAO, 2019). Perishable items, such as fruits and vegetables, are particularly prone to maltreatment due to their fragility.

Furthermore, utilizing improper packing materials or overloading containers might lead to increased losses during travel and storage. Environmental variables such as high temperatures, humidity, and a lack of sufficient ventilation during storage all contribute to degradation. For example, grains kept in non-airtight containers are vulnerable to insect infestations and mold development (Kitinoja and Kader, 2002). Inadequate worker training and restricted access to infrastructure and technology are major causes of these inefficiencies, particularly in developing nations. To limit the effects of incorrect handling, best practices such as careful sorting, adequate packing, and sanitary handling settings must be followed. Investments in post-harvest infrastructure, including as cold storage and training programs, can help to drastically minimize losses. Government measures that promote farmer knowledge and access to advanced technology are also essential (WRI, 2013).

Inadequate packaging

Proper packing is crucial for preserving fresh fruits and vegetables and reducing losses. Inadequate packaging practices and inappropriate packing materials lead to severe post-harvest losses. Using low-quality packaging materials might lead to premature deterioration of fresh products due to inadequate protection against harm. Using low-quality packaging materials is frequent, particularly in poor and impoverished countries (Kitinoja, 2010).

Post Harvest Technologies

Horticultural produces are perishable and require proper harvesting and handling to prevent losses from physical, mechanical, and microbiological factors. Standardized harvesting procedures and storage conditions are necessary for extending product shelf life. Post-harvest technologies include strategies and equipment for preserving the quality, extending the shelf life, and reducing losses from agricultural produce after harvest. These technologies handle crucial issues including spoilage, microbiological contamination, and physical damage (FAO, 2013). Cold chain systems, which keep perishable foods at the right temperature, and modified environment packaging, which changes oxygen and carbon dioxide levels to reduce spoiling, are two important advances (Kitinoja, 2012). Advanced sorting and grading machinery maintain consistency and minimize handling damage, while technologies such as solar dryers and hermetic storage systems avoid grain rotting and insect infestation. Real-time monitoring of storage conditions by digital instruments like IoT sensors ensures ideal surroundings. Implementing these technologies can help to decrease post-harvest losses, improve food quality, and increase supply chain efficiency. Their acceptance, particularly in poor countries, is dependent on government assistance, farmer education, and access to cost-effective solutions. Recent technologies to extend shelf-life and quality of the produce is:

Drying

Dehydration, the oldest method of food preservation, involves removing moisture to increase its shelf life. This approach progressively reduces the moisture level in fruit tissue, reducing the risk of decomposition (Gupta, 1984). There are several drying processes available, including: Dehydrator dryers use artificial heat to manage humidity, temperature, and airflow. Oven dryers adjust temperature using their heat source. Traditional drying processes have been used, such as low-temperature drying (15-50°C) and high-temperature drying (over 50°C). Another method for drying involves freezing liquids, such as fruit juice, at temperatures ranging from -10 to -40°C (Aravindh, 2015).

Solar drying: Sun drying is a popular method for drying agricultural goods in low- and middle-income countries (LMICs). However, it may not be feasible during the harvest season or in humid areas (Mendoza *et al.,* 2017; Bradford *et al.,* 2018). Traditional open air drying methods, including the ground, trays, baskets, paper or plastic sheets, and rooftops, expose items to pests, predation, theft, and contamination (Nagwekar *et al.,* 2020). According to (Chua and Chou, 2003), solar dryers are quicker, more sanitary, maintain nutritional value, and are cost-effective compared to open air drying.

Hermetic storage: Hermetic storage is essential for preserving dried commodities after harvest. It inhibits moisture penetration, fungal development, insect activity, and creates a low-oxygen environment (Murdock *et al.,* 2012; Alemayehu *et al.,* 2023). Hermetically storing dried horticultural crops preserves their visual and organoleptic qualities (Villers *et al.,* 2008). To ensure successful hermetic storage, products must be adequately dried (Tubbs *et al.,* 2016).

Canning

Preserving vegetables in a sealed container increases its shelf life. This method involves storing perishable acidic fruits and vegetables in a container and heating them. To peel a tomato, submerge it in boiling water for a minute before placing it in a container containing acetic acid, Vitamin C, or citric acid (Parnell *et al.,* 2004).

Packaging

Leafy vegetables are among the most perishable types of horticulture crops. Due to their high surface-to-volume ratio and low epidermal resistance to water transport, they quickly lose water and wilt, resulting in considerable loss of saleable weight as well as visual, textural and nutritional quality. Perforated or non-perforated polyethylene bags are a practical way for smallholder farmers and traders to maintain high relative humidity and reduce water loss in horticultural commodities. High humidity refrigeration is ideal for less perishable commodities. Many countries have banned the use of these bags in food marketing due to their harmful impact on the environment (Nielsen *et al.,* 2019). Compostable and biodegradable polymers have been used as alternatives to HDPE bags. However, these polymers have higher water vapor transmission rates and are less effective in preventing water loss. Additionally, they are significantly more expensive. Integrating plastic crates into value chains might be challenging in LMICs. The feasibility of integrating crates into a value chain depends on factors such as ownership, return system, market premium, and negotiation with transporters. Smallholder farmers' risk aversion and social norms also play a role (van Wagenberg *et al.,* 2019).

Modified Atmospheric Packaging: (Mohamed *et al.,* 1996) found that modified atmospheric packaging (MAP) extended the shelf life of fruits. Fruits stored at 100°C and 150°C in MAP lasted 4 and 3 weeks, respectively, significantly longer than the one-week shelf life without MAP. (Sozzi *et al.,* 1999) demonstrated that low oxygen (3%) and high CO2 (20%) levels in MAP reduced ethylene production, slowed enzyme activity, and improved tomato quality. (Chonchenchob *et al.,* 2007) reported that a combination of 6% oxygen and 14% CO2 in MAP extended the shelf life of fresh-cut pineapple to 7 days at 100°C. (Ayhan *et al.,* 2008) found that storing carrots at a mixture of 80% oxygen and 10% CO2 increased shelf life and retained improved physiological qualities compared to 5% oxygen.

Nanotechnology in Packaging: Nanotechnology in fruit packaging improves protection and shelf life. Incorporating small particles into packing materials strengthens gas and moisture barriers, minimizing spoilage and degradation. Nanotechnology provides fine control over packaging qualities, resulting in a more efficient and personalized solution to preserve fruit quality (Sharma *et al.,* 2017). This concept aims to reduce food waste and improve post-harvest sustainability by keeping fruits fresher for longer durations during storage and transit. Beyond artificial advancements, nanotechnology celebrates the richness of natural resources. Natural ingredients renowned for their antibacterial and antioxidant properties, including as plant extracts, essential oils, and a range of bioactive chemicals, take center stage in this paradigm (Lutz and Coradi, 2022). These bioactive components, which behave similarly to nature's superheroes, combine with coatings to form a plant-based shield (Rodrigues *et al.,* 2022). This adaptable bioactive coating is a long-term means of preserving fruit quality while also protecting against microbial foes. As a result, the bioactive coating functions as a symbiotic guardian for the fruit such as peaches actively preventing degradation and ensuring that the fruit remains fresh throughout the storage process (Kondle *et al.,* 2022; Khetabi *et al.,* 2022).

Controlled Atmosphere (CA) Storage

The "modified atmosphere" contains traces of additional gases, including 21% O2, 78% N2, and 0.03% CO2. It is based on the concept of establishing an artificial environment in storage with high CO2 concentrations and low O2 levels to slow down respiration and ripening. By delaying breathing, aging is postponed. Litchi when kept at 1 °C in a controlled environment (3-5% CO2 and 3-5% O2) at 90% RH, exhibited browning control and fruit quality retention for up to 30 days (Lin *et al.,* 1988). CA storage is useful for transporting a huge quantity of fruit.

Temperature-Controlled Storage Technologies

Temperature-controlled storage (TCS) solutions are critical to maintaining the quality, safety, and efficacy of perishable foods, medicines, and other temperature-sensitive items. Refrigeration, insulation, temperature and humidity control systems, monitoring and alarm systems, and energy-efficient technologies are examples of critical technologies. These technologies are critical for many sectors, including medicines, food, chemicals, and healthcare. However, concerns like as energy usage, dependability, and cost-effectiveness must be solved. Continued technological developments, such as better insulating materials and energy-efficient refrigeration systems, are required to increase the efficiency and sustainability of TCS. The government offers subsidies to entrepreneurs that want to run a cold storage facility for business purposes. Additionally, the National Horticulture Board offers financial help for cold storage. These incentives boost interest in the cold chain industry. Beneficiaries include cooperative societies, agricultural produce and sale committees, agricultural industry cooperatives, and farmer cooperatives. Cold storage capacity should be 5000 Mt, and growth should not exceed two crores (Karthiga, 2012).

Cold Chain Management

Effective cold chain management is crucial in today's perishable industries. According to (Singh *et al.,* 2018), the process of planning, implementing, and controlling the flow and storage of perishable goods, related services, and information enhances customer value while ensuring low costs. Perishable items require precise temperature control throughout the supply chain, from manufacture to customer touchpoints. The Cold Chain contains perishable items such as fresh agricultural products, frozen food, seafood, chemicals, medicinal medications, and photographic film. According to (Liu *et al.,* 2020), the Cold Chain market is divided into five groups based on end-use: fruits and vegetables, bakery and confectionery, dairy and frozen desserts, fish and shellfish, and medicines. Effective temperature management is crucial for reducing post-harvest losses in fresh fruits and vegetables. High temperatures during harvest, storage, and transport can lead to increased metabolic activity, water loss, ethylene production, and decay of fruits and vegetables, reducing shelf-life and nutritional value (Yahia and Elansari, 2011).

Evaporative cooling

The Zero Energy Cooling Chamber (ZECC) is a passive evaporative cooling chamber created in India in the early 1980s. It consists of a rectangular room encircled by a double brick wall, with sand filling the gap (Roy and Khurdiya, 1982). The product is placed into the chamber with a cover on top. Evaporation from the brick surface cools the chamber, while water trickles into the sand. In evaporative cooling, dry air absorbs water and cools both itself and the water. Cooling capability is greatest when the ambient air is low in humidity and temperatures are moderate (Kumar *et al.,* 2018). Evaporative cooling systems are most commonly used for post-harvest management, in which external air travels through wetted material into a storage chamber (Manuwa and Odey, 2012). Passive evaporative cooling systems transfer heat by conduction and convection, while active systems employ an external device to drive air through the wetted material, enhancing cooling efficiency (Ndukwu and Manuwa, 2014). Evaporative cooling is effective for short-term storage of fruits and vegetables in appropriate climates, as well as precooling items (Amwoka *et al.,* 2021). Evaporative cooling has constraints such as limited water availability and limited cooling capability in high humidity conditions (Verploe *et al.,* 2019).

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Traditional cooling

Mechanical refrigeration is the primary method for maintaining the cold chain for most horticultural goods. Standard compressor/evaporator refrigeration is more sustainable than earlier refrigerants due to its high efficiency (Oxtoby *et al.,* 2011). The necessity for cooling and cold storage emphasizes the need of having access to reliable and economical energy, whether through an electric grid or freestanding solutions like solar, solar with batteries, or generators. Solar-powered cold storage is currently considered key infrastructure for reducing postharvest losses for smallholder farmers (UNIDO and REEEP, 2020). Standard refrigerated equipment, insulated chambers, and solar power supply are too expensive for smallholder farmers in low- and middle-income countries.

Coldrooms

The efficacy of a refrigerated room is entirely reliant on the quality of its insulation and the presence of a robust vapor barrier. Small commercial coldrooms employ polystyrene or polyurethane panels, whereas larger rooms use spray-on polyurethane foam for high-quality insulation and vapor barrier. Polyurethane foam also has structural qualities, and extremely large insulated rooms have been built by spraying polyurethane foam inside an inflated balloon, then spraying a layer of concrete over reinforcing steel (Bomberg and Kumaran, 1999). In Nepal, government subsidies enabled R&D Innovative Solutions, Inc. to give 150 CoolBotTM chill rooms to horticultural growers who could not otherwise afford them. Smallholder kiwi fruit producers that have access to cold storage saw lower losses. Some of these rooms had insufficient insulation, but the improvement in stored product quality was large enough to provide positive returns. Another example of government backing is an Uzbek government preferential financing scheme for cold storage, which was launched with the assistance of foreign financial institutions and resulted in a more than 1000-fold increase in the country's cold storage capacity in 2011 (Tracy and Taylor, 2017). Government funding can be important to the expansion of a cold chain. However, for sustainability, consistent market demand for goods from upgraded cold storage facilities is required (Amwoka *et al.,* 2021).

Liquid nitrogen

(Linde, 2023) and (Yun *et al.,* 2018) recommend using liquid nitrogen as a refrigeration method for storage and transportation. However, since the boiling point of liquid nitrogen is −196 ºC, the evaporation rate must be carefully controlled to prevent the stored products from freezing (Valeriu *et al.,* 2010). Liquid nitrogen cooling provides several advantages over mechanical cooling, such as fewer mechanical components, less need for refrigerants that might harm ozone, and quieter operation. However, in low- and middle-income countries (LMICs) with limited infrastructure, producing and transporting liquid nitrogen may not be feasible or cost-effective.

Thermoelectric cooling

The Peltier effect is used in thermoelectric cooling to produce a temperature differential between two dissimilar materials, such as copper or zinc (OEERE, 2023). A Peltier cooler is a solid-state active heat pump comprising multiple parallel connections between two ceramic plates, and transfers heat from one side of the device to the other when a DC voltage is applied. Peltier coolers are commonly employed in small-scale cooling applications, such as high-speed computers, microscope stages, portable beer coolers, and so on. These devices have lower efficiency than heat pumps, but they are affordable and exceedingly simple. A bank of Peltier devices with heat exchangers and fans (internal and exterior) can function as a tiny air conditioner.

Advancements in Cold Chain Management and Logistics

Postharvest technology focuses on maintaining a cold chain from harvest to market and optimizing storage temperatures for fruits and vegetables (Kader, 2003). Recent years have witnessed significant advancements in cold chain management, driven by technological innovations and increasing consumer demand for fresh, high-quality products. One of the key advancements is the widespread adoption of Internet of Things (IoT) devices and sensors, which enable real-time monitoring of temperature, humidity, and other critical parameters throughout the supply chain. This data-driven approach allows for proactive issue resolution, minimizing product loss and ensuring optimal product quality. Additionally, blockchain technology is emerging as a powerful tool for enhancing transparency and traceability in cold chain operations. By creating a secure, immutable record of product movement and temperature history, blockchain can help build trust among stakeholders and mitigate risks associated with product contamination or spoilage. Furthermore, the development of sustainable refrigeration technologies, such as energy-efficient cooling systems and natural refrigerants, is contributing to a greener and more environmentally friendly cold chain. By reducing carbon emissions and minimizing the environmental impact, these technologies promote sustainable practices in the food and pharmaceutical industries. Theoretical models may depict ideal storage and transportation scenarios, but the real world is often less organized. Monitoring is crucial for sophisticated logistics systems due to frequent departures from ideal conditions (Jedermann *et al.,* 2017).

Summary and Conclusion

Post-harvest technologies and cold chain management play a crucial role in maintaining the quality, safety, and marketability of perishable products, including fruits, vegetables, and pharmaceuticals. Effective post-harvest handling begins at the farm level and involves practices such as sorting, cleaning, packaging, and pre-cooling. These steps reduce spoilage and prepare goods for efficient storage and transport. The dry chain, a subset of post-harvest technologies, focuses on moisture control to prevent microbial growth and spoilage, especially for grains and seeds. The cold chain, by contrast, utilizes temperature regulation to preserve perishables. Innovations in digital technologies such as IoT, AI, and blockchain enhance monitoring, optimize conditions, and ensure traceability across the supply chain. Emerging tools like digital twins and advanced sensors offer real-time quality assessments, enabling proactive interventions.

The future of post-harvest and cold chain management is promising, with advancements in sustainable technologies and digital solutions. Enhanced integration of IoT and AI will enable more efficient monitoring, while sustainable refrigeration methods aim to reduce environmental impacts. The combination of dry and cold chain methodologies could address specific challenges in preserving various commodities, ultimately reducing food losses and improving global food security. Continued research and adoption of cutting-edge technologies will be pivotal in making these systems more resilient and accessible, particularly in developing regions.

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