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From Farm to Fork: The Importance of Refrigerated Cold Chain Management

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SUMMARY

The cold chain plays a crucial role in preserving and transporting perishable foods within specific temperature ranges, helping to slow biological decay and ensure that consumers receive safe, high-quality products. However, studies indicate that the cold chain often operates below optimal efficiency, with frequent instances of temperature abuse both above and below ideal ranges leading to increased food waste and safety concerns. Key weaknesses identified include pre-cooling processes, ground transportation operations, storage during retail display, and domestic refrigeration practices. To advance the cold chain on a global scale, the proposal includes a combination of prospective experimental research, modeling studies on pre-cooling uniformity, and the development of responsive food inventory management systems, particularly focusing on cold chains in developing countries.

INTRODUCTION

A cold chain is an uninterrupted-temperature controlled transport and storage system of refrigerated goods between upstream suppliers and consumers designed to maintain the quality and safety of food products (Montanari, 2008; Taoukis et al., 2016). Unexpected temperature changes or abuses in food cold chain can lead to compromised food safety and food quality that ultimately can result in loss of consumer confidence and increased levels of food waste. It has been reported that roughly one-third of global food production is wasted annually (Gustavsson et al., 2011). Food waste refers to an unacceptable level of quality of food or food discarded by retailers or consumers due to microbial rot, disease or insect damage. A high share of these losses is related to poor post-harvest handling, lack of proper facilities, and insufficient training for operators in the cold chain. In the last decade, cold chain problems have been investigated and reviewed (Koutsoumanis & Gougouli, 2015; Mercier et al., 2017; Montanari, 2008; Taoukis et al., 2016). Perishable products require a precise temperature-controlled atmosphere along the entire supply chain (SC), from production to consumer touch points. This requirement, commonly denoted as "CC", refers to a post-production SC for perishable and temperature sensitive goods, and is specifically designed to keep these products in a conditioned environment (i.e., within optimal temperature and humidity range) to guarantee product safety, preserve value and maximize commercial potential (Salin and Nayga, 2003; Joshi et al., 2009; Rodrigue, 2014). The perishability of goods is a key point of this definition. In other words, refrigerated transportation and storage are two fundamental aspects to prevent deterioration of the product quality (James and James, 2010). The Cold Chain includes a variety of perishable products, namely fresh agricultural products, frozen food, seafood, chemicals and pharmaceutical drugs and photographic film (Allied Market Research, 2019). Regarding end-use, the Cold chain market is classified into five main categories, namely, fruits and vegetables, bakery and confectionary, dairy and frozen desserts, fish and seafood, drug and pharmaceuticals (Liu et al., 2020). This classification integrates two main Cold chain fields, namely, food cold chain (FCC) and pharmaceutical cold chain (PCC) (Herjolfsson, 2019).

The Role of Temperature Control

Temperature control is essential in preserving the freshness and safety of perishable food items. Foods such as dairy products, meats, fruits, and vegetables are highly susceptible to spoilage if not kept within their required temperature ranges. When food is stored at incorrect temperatures, it can lead to the growth of harmful bacteria, which can cause food borne illnesses. For instance, the bacteria *Listeria monocytogenes* can grow at refrigeration temperatures and can be particularly dangerous for pregnant women, newborns, and individuals with weakened immune systems. Maintaining the correct temperature throughout the supply chain helps to minimize the risk of bacterial growth and ensures that food remains safe for consumption. This involves not only keeping food cold but also ensuring that it does not freeze if it is not meant to. For example, certain fruits and vegetables can suffer from cold damage if stored at temperatures that are too low, leading to a loss of texture and flavor (www.foodpoisoningnews.com).

Cold Chain Management

Cold chain management refers to the process of controlling the temperature of perishable products from the point of origin through the distribution chain to the final consumer. This includes transportation, storage, and handling of products. Effective cold chain management is crucial for maintaining the quality and safety of food products.

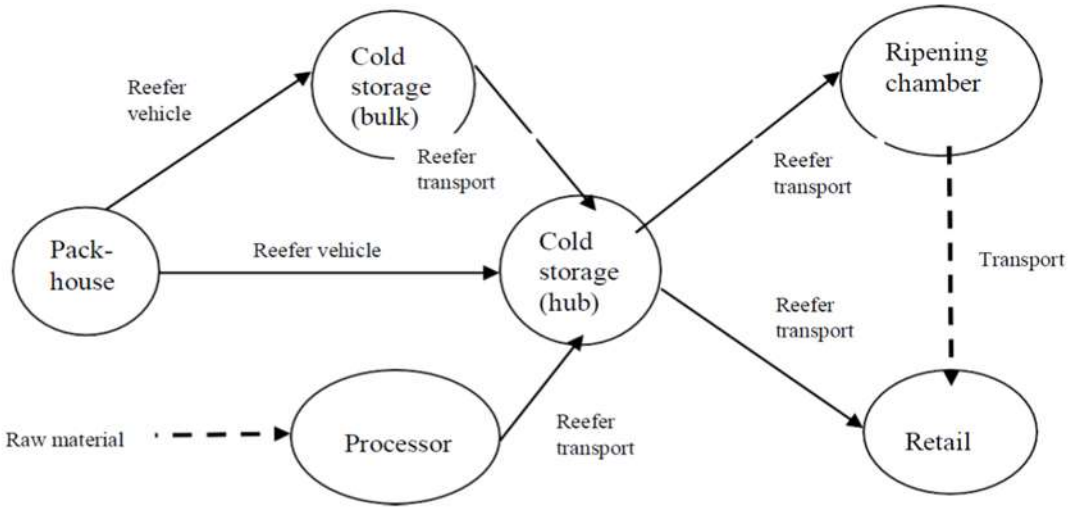

Fig.1. Schematic depiction of the flow of produce in a typical cold-chain (Source: GoI, 2018)

One of the primary benefits of cold chain management is the reduction of food waste. According to the Food and Agriculture Organization (FAO), approximately one-third of all food produced for human consumption is lost or wasted. A significant portion of this waste occurs due to improper temperature control during transportation and storage. By maintaining the correct temperatures, cold chain management helps to extend the shelf life of perishable products, reducing waste and ensuring that more food reaches consumers (www.foodpoisoningnews.com). The operation and maintenance of 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 (Lange et al., 2016), 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 (USAID,2009). 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 (National Horticulture Board, 2010). 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 (Guo 2020). Manufacturers need to understand the characteristics of their products and ensure optimal conditions throughout the distribution process: (Rafik, 2007)

- Temperature necessity inside the cargo and maintenance
- Defining, maintaining and ensuring temperature specifications during transport
- Transportation study
- Acceptance criteria for storage and transport of material between sites
- Validation of transport carrier
- Standard operating procedures, records and documentation to ensure the conditions
- Time out of refrigeration
- transport conditions at various stages of distribution including: manufacturer to third party between two sites or to and from a filing contractor
- Assurance that temperature and humidity controls are monitored during shipping
- Standard practice for performance testing of transport containers

The integrity of cargo concerns the conditions of loading, reloading and unloading of goods in a way that guarantees the minimizing of risk of product quality loss during the transport. It includes additionally the supplying

of adequate packages and packaging techniques. Whereas the integrity of transport is characterized by the actions and treatments to provide constant transport temperature for products sensitive to the temperature fluctuations (Klecha and Zimne 2014).

GROUPS OF PRODUCTS IN COLD CHAIN

The goods requiring transportation and storing in precisely specified temperature can be included in several different groups. Among them, there are food products i.e. meat, dairy products, fruit and vegetables, deep-frozen products, flowers and plants, as well as products of dissimilar sectors, i.e. chemicals, pharmaceuticals and other medical purposes goods.

Industries using cold supply chain:

- Fruits and vegetables
- Floriculture
- Meat and marine products
- Pharmaceutical Products
- Dairy products
- Ice cream sector and confectionery

According to temperature range the products should be kept in, the five groups of cargo can be distinguished:

- Banana (12^{o}C do 14^{o}C), a group characterized by temperature range enabling to monitor ripening of fruit,
- Pharmaceutical (2^{o}C do 8^{o}C), for most specialty pharmaceuticals including vaccines
- Chill (2^{o}C do 4^{o}C), products for which the average storage temperature include fresh fruits and vegetables, dairy products, meat products
- Frozen (-16^{o}C do -20^{o}C), category for frozen products including meat
- Deep freeze (-28^{o}C do -30^{o}C), group with the lowest achievable temperature, designed to transport seafood(Wojciechowski, 2014).

Future Trends in Cold Chain Logistics-

Technological Innovations

Advancements in technology have significantly improved the efficiency and reliability of cold chain management. For instance, the use of Internet of Things (IoT) devices allows for real-time monitoring of temperature and humidity levels throughout the supply chain. These devices can send alerts if temperatures deviate from the acceptable range, enabling quick corrective actions to be taken. Additionally, block chain technology is being used to enhance transparency and traceability in the cold chain, ensuring that all parties involved can verify the conditions under which food has been stored and transported (www.foodpoisoningnews.com).

Technological innovations in the cold chain are transforming how perishable goods are preserved and transported. Key advancements include:

IoT Sensors: Internet of Things (IoT) devices enable real-time monitoring of temperature and humidity levels throughout the supply chain, providing alerts for any deviations from optimal conditions.

Block chain Technology: Block chain enhances traceability and transparency, allowing all stakeholders to track the journey of products and verify their safety and quality.

Smart Refrigeration Systems: Advanced refrigeration units with smart controls optimize energy use and maintain consistent temperatures, improving overall efficiency.

Mobile applications: Apps for managing inventory and monitoring conditions allow businesses to respond quickly to potential issues and improve logistics planning.

RFID Technology: Radio-frequency identification (RFID) tags streamline tracking and inventory management, reducing losses and ensuring compliance with temperature requirements.

Automated Cold Storage: Robotics and automation in cold storage facilities enhance efficiency in handling and storing products, minimizing human error and energy consumption.

Thermal Packaging Solutions: Innovative packaging materials that provide better insulation help maintain the required temperature during transport and storage.

Drones and Autonomous Vehicles: These technologies are being explored for last-mile delivery of temperature-sensitive products, offering flexibility and speed.

These innovations aim to enhance the reliability, efficiency, and safety of the cold chain, ultimately reducing food waste and improving product quality.

Reducing the carbon footprint-

The Cold Chain Logistics (CCL) sector is known for its high energy usage due to processes like rapid freezing of products, maintaining them at low temperatures, processing them in cold conditions, selling, and transporting them in a way that keeps them cold. This not only uses a lot of energy but also results in a large amount of carbon emissions. Essentially, it is an industry that requires a lot of power and has a significant environmental impact because of its need to keep things cold from production to delivery. Therefore, a low-carbon CCL industry has attracted significant attention from government, enterprises, professional, and residents, and reducing energy consumption and carbon emissions has become a ubiquitous trend in the CCL industry (Zhang, Tseng, et al., 2019).

A cold chain in food processing is essential for reducing the carbon footprint in several ways: -

Minimizing Food Waste: - By maintaining optimal temperatures throughout the supply chain, a cold chain helps keep food fresh for longer periods. This reduces spoilage and waste, meaning less food ends up in landfills. When food decomposes in landfills, it produces methane, a potent greenhouse gas. Therefore, less waste means fewer methane emissions.

Efficient Transportation: - Modern cold chain logistics often involve advanced, energy-efficient refrigeration systems and vehicles. These systems use less energy and emit fewer greenhouse gases compared to older models. By optimizing routes and loads, cold chains can further reduce fuel consumption and emissions during transportation.

Local Sourcing: - A well-managed cold chain allows for the storage and transportation of locally produced food over longer periods. This reduces the need for importing food from distant locations, which involves extensive transportation and higher emissions. Supporting local food systems also helps cut down on the carbon footprint associated with long-haul shipping.

Energy Efficiency: - Cold chain technologies are continually improving, with innovations aimed at reducing energy consumption. For instance, solar-powered refrigeration units and other renewable energy solutions are becoming more common. These technologies reduce the reliance on fossil fuels, thus lowering the carbon footprint.

Preserving Nutritional Value: - Proper temperature control helps preserve the nutritional quality of food, reducing the need for energy-intensive food processing methods. This not only conserves energy but also ensures that consumers get high-quality, nutritious food, contributing to overall sustainability.

Supply Chain Optimization: - Implementing an effective cold chain system can streamline the supply chain, making it more efficient. This includes better inventory management and reduced overproduction, both of which contribute to lower energy use and emissions.

CONCLUSION

In conclusion, cold chain management is essential for ensuring the safety, quality, and sustainability of our food supply. By maintaining precise temperature and humidity conditions from farm to consumer, cold chain minimizes food waste, preserves nutritional value, and mitigates the risk of food borne illnesses. Emerging technologies such as IoT, cloud computing, big data, block chain, and AI are transforming cold chain into more efficient and intelligent systems. These innovations facilitate real-time monitoring, control, and optimization of the supply chain, enhancing both transparency and efficiency. Looking ahead, reducing the carbon footprint of cold chain management is a top priority, with a focus on energy-efficient refrigeration and sustainable practices. By integrating these technologies and approaches, we can improve food safety, decrease environmental impact, and effectively meet the growing demands of the global food market.

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