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Enhancing Cold Chain Logistics: A Framework for Advanced Temperature Monitoring in Transportation and Storage

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Abstract: In the face of the increasingly demanding of goods transportation and storage, the orchestration of cold chain logistics emerges as a critical and multifaceted endeavor. This study, addressing a notable gap in literature, establishes a comprehensive framework for temperature monitoring within cold chain logistics, focusing particularly on transportation and warehousing aspects. The complexity of managing temperature-sensitive goods is amplified by the burgeoning number of entities involved in this sector, underscoring the need for a robust monitoring approach. Recent global challenges have precipitated a series of disruptive events, further complicating the reliable transport of temperature-sensitive commodities. In light of these challenges, the necessity for meticulous temperature control during both transportation and warehousing phases is paramount; lapses in this regard could lead to grave consequences. A thorough analysis of existing cold chain delivery systems was conducted, alongside an examination of various temperature monitoring devices utilized in vehicle cargo compartments and storage facilities. The study not only scrutinizes current trends but also introduces novel solutions for effective monitoring. By exploring and evaluating these elements, the research contributes significantly to both theoretical and practical spheres, offering a solid foundation for future investigations and guidance for practitioners and decision-makers in the field. This exploration revealed the imperative for advanced sensor technologies and integrated data management systems, capable of providing real-time, accurate temperature readings throughout the entire cold chain process. The integration of smart transportation solutions, leveraging Internet of Things (IoT) technology, emerges as a pivotal factor in enhancing the reliability and efficiency of temperature monitoring. Additionally, the study underscores the importance of standardized protocols and practices across the industry to ensure consistency and reliability in temperature management. In conclusion, the framework proposed in this study not only addresses existing challenges in cold chain logistics but also paves the way for innovative approaches in temperature monitoring, fostering enhanced quality control and safety in the transportation and storage of temperature-sensitive goods.

Keywords: Cold chain logistics; Temperature monitoring; Sensor technology; Transportation; Warehousing; Internet of Things (IoT); Data management

1 Introduction

The concept and technology for temperature-sensitive product control have been established for decades. However, the development of cold chain systems, especially in terms of government policy, represents a relatively new concept. Cold chain systems can be observed as a business function in the global value chain rather than as an industry. The United States has a competitive advantage in cold chain systems, thanks to some of the most advanced logistics management technologies and services in the world. In developing economies, initial opportunities for cold chain development include warehouse design, logistics operations, and technology, including logistics providers as potential service providers, where this can contribute to the efficient development of infrastructure. In countries with unreliable electrical power, unique or alternative solutions are required to maintain temperature control in warehouses. Improper organization of the cold chain or its absence in the business world is deemed unacceptable today for several reasons.

Food loss is one of them and represents a significant economic, environmental, and social problem. One-third of the food produced worldwide for human consumption never reaches consumers [1]. This not only has significant implications for climate and human health, but the annual economic value of this loss continues to rise. In countries with not-so-well-organized cold chains, 200 million tons of food are lost before it reaches the market. Additionally, in the pharmaceutical industry, the cold chain is one of the desirable solutions, and in the future, it may become mandatory, given the predicted 41% growth in the global pharmaceutical industry from 2015 to 2020. This allows for the potential improvement of the quality of life in developing countries and the provision of cutting-edge medical and pharmaceutical products to those in need worldwide [2].

In order for shipments to reach various regions and remote locations, longer travel routes are inevitable. Conditions on the journey are often unpredictable, making it more likely that the shipment will traverse different climatic zones and that the transportation infrastructure will be less developed. Freight forwarders must contend with a greater number of regulatory requirements, increased variations in customs regimes, and uncertain local transport options. All these factors can lead to high costs for the successful transportation of a shipment. What is certain is that the cost of an unsuccessfully transported shipment is much higher. Under these challenging circumstances, successful deliveries rely on the selection of appropriate packaging for each type of material and the conditions that may occur during transit [3].

The continuous monitoring of transport vehicles, ensuring the tracking of crucial parameters, plays a pivotal role in facilitating proper transportation to preserve the integrity and quality of products. This aspect constitutes an additional critical factor that should be prioritized in the pursuit of successful deliveries. Despite companies often placing reliance on packaging for shipments, they frequently overlook the significance of monitoring. Packaging, while crucial, represents just one facet of a securely transported, temperature-controlled shipment. Even after selecting the most suitable packaging solution, numerous potential variables and uncertainties during transport can lead to exceeding the temperature range the packaging is designed for, resulting in product spoilage. Hence, it is imperative to engage in continuous temperature monitoring, providing insights and enabling prompt corrective measures in the event of temperature range exceedance. In addition to monitoring temperature throughout the transportation process, tracking during storage is equally vital, as temperature-sensitive products can be susceptible to spoilage during reception or storage. Hence, it is imperative to establish optimal conditions for the storage of such goods. Achieving suitable storage conditions necessitates the utilization of proper temperature measuring and monitoring devices. Having all that was previously said in mind, this paper aims to propose a framework for monitoring temperature in cold chains, with special emphasis on transportation and warehousing processes.

The paper is organized as follows: In the second section, the significance of monitoring and temperature tracking in cold chains is described in detail. Section three presents the transportation means and units used for goods transportation in cold chains. The next two sections (four and five) present the devices used for monitoring and tracking temperature conditions in transportation and warehouses, respectively. In the sixth section, discussion as well as cold chain trends regarding transportation and warehousing are discussed. Finally, in the last section, concluding remarks, limitations, and future research directions are outlined.

2 The Significance of Monitoring and Temperature Tracking in the Cold Chain

The evolution of temperature-controlled transportation dates back to the 1800s, when early carriers resorted to placing ice and salt beneath temperature-sensitive goods in train compartments. Regrettably, this method proved highly inefficient, resulting in substantial losses of merchandise and diminished profitability. The turn of the 1900s witnessed the development of more efficient transportation techniques, notably the advent of refrigerated transport. Technological advancements played a crucial role in fostering the establishment of the cold chain, thereby catalyzing the expansion of the mass industry [4]. During the initial stages of temperature-controlled transportation for pharmaceutical products, carriers utilized expanded polystyrene coupled with water-based gel packs. While this packaging was validated for specific time periods and temperature ranges, its cost-effectiveness was overshadowed by its tendency, even with passive temperature control inserts, to experience excursions beyond the intended temperature ranges during transit. Logistic service providers found themselves needing to validate numerous assumptions regarding whether the product remained within the specified temperature range during transport, leading to potential delays for manufacturers [5].

Undoubtedly, the progression of packaging within the cold chain, evolving over time, holds little significance without tools ensuring the shipment's integrity. Research suggests that the majority of temperature excursions occur within a 1.6 km radius from the destination, underscoring the necessity for technology capable of monitoring the shipment's temperature throughout the entire delivery process, encompassing transportation and storage.

For numerous product categories, transporting them under temperature-controlled conditions is not a choice but an absolute imperative. The pharmaceutical industry forecasts that by 2021, the value of pharmaceutical cold chain logistics will reach $16.6 billion [2]. Exposure of cargo to temperature factors exceeding prescribed limits can lead to damage. While this damage is apparent in some cases, such as with bananas, in other scenarios, like transporting vaccines, the damage may not be immediately evident, yet it unquestionably jeopardizes vaccine efficacy. For specific products, even a brief excursion beyond designated temperature ranges can markedly diminish their shelf life.

Organizations that engage in the transportation of temperature-sensitive products frequently establish an acceptable temperature range. Nevertheless, even if it can be proven that the product was subjected to conditions beyond the agreed-upon ones, elucidating where this occurred and consequently ascertaining responsibility can pose a considerably more challenging task. The only effective means is to maintain a chronological record of temperature conditions throughout the transit. The adoption of monitoring practices became prevalent in the business world in the mid-2000s, with the incorporation of high-tech data loggers or monitors into shipments to alleviate risks and provide a display of the temperature history during transport. The impetuses for advancements in temperature monitoring were [5]:

•Stringent regulatory requirements globally;

•The escalating value of pharmaceuticals and other commodities;

•The demand for new temperature ranges.

Technological advancements in these domains have given rise to an increasing array of products necessitating a temperature-controlled milieu to preserve their integrity and efficacy [4]. A temperature-controlled environment encompasses any setting where the temperature is actively or passively regulated at a level different from that of the surrounding environment, within precisely defined limits [6]. Even though a lot of temperature-sensitive goods are made, the cold chain's full potential is still mostly untapped. This is because there are too many individual refrigeration units, too few investments in infrastructure like the transportation network, too few people who know how to handle perishable goods properly, and poor service from warehouse owners or carriers, which leads to compromise [7].

The Food and Agriculture Organization (FAO) projects a 70% increase in food production and availability by 2050. This projection emphasizes the need for swift action to secure an ample food supply, given the expected global population of over 9 billion by 2050, which poses a considerable challenge. Thus, it is imperative to explore all possible avenues for progress, particularly in mitigating food losses attributed to the aforementioned challenges. The losses of temperature-sensitive food products are most pronounced in developing countries, where more than 80% of the world's population resides, resulting in the loss of approximately a quarter of the produced food due to the absence of a comprehensive cold chain. These substantial post-harvest losses have repercussions on the resilience of rural economies, significantly widening the disparity between consumer prices and the earnings received by farmers. Such losses not only limit consumer access to products but also diminish the income of farmers, discouraging them from continued production and market supply.

Temperature excursion refers to an occurrence where the product is subjected to temperatures beyond the range specified for storage and/or transportation. The temperature limits for storage and transportation may be the same or different and are determined by the manufacturer based on stability data [6]. Entities involved in transportation services, such as freight forwarders and other stakeholders, should adhere to Service Level Agreements (SLAs). SLAs outline the targeted and minimum levels of performance, services, operations, or other attributes as per the user's requirements. They can be legally binding or serve an informative purpose. SLAs may also establish targets and minimum performance levels, operations, or other service attributes. In terms of performance monitoring and reporting, specific attention should be given to the following [6]:

•Managing changes in key personnel;

•Benchmarking services;

•Monitoring and reporting mechanisms;

•Conducting service review and evaluation meetings.

Key factors for maintaining the cold chain are clearly defined below:

(1) Product preparation - A range of parameters is utilized to evaluate the characteristics of transporting temperature-sensitive products. Special attention is required for weather conditions before transportation, particularly for products exposed to extreme cold or hot influences during transit. The use of refrigerated vehicles with their own power units commonly addresses such concerns.

(2) Transportation options - Various crucial factors are taken into account when determining the transportation of shipments. Factors such as the distance between the initial and final destinations, size and weight of the shipment, required external temperature conditions, and perishability of the products impact the available transportation options. Short distances can be covered by vans or trucks, while longer journeys may necessitate the use of airplanes or container ships. The cost-to-perishability ratio also becomes a significant consideration.

(3) Real-time inspection of procedures - Due to the heightened sensitivity of cold chain products to weather factors compared to other goods, they undergo thorough inspection, particularly during procedures tailored for the cold chain. Monitoring during transportation assumes a pivotal role in ensuring the integrity of the cold chain in this context.

(4) "Last mile" - This term is employed to describe the delivery of a shipment to its destination in the final,

often termed "last mile" segment of transportation. Given the critical nature of delivery time and the importance of ensuring that products reach their intended destination, securing warehouse space at the destination is imperative.

(5) Ensuring integrity and quality assurance - This phase of establishing the required temperature involves a logistical process that fosters trust among partners but also carries responsibility, particularly when accountability for a damaged shipment is at stake. In the event of any issues, efforts should be directed towards identifying the source and determining corrective measures.

Monitoring the transit of vehicles offers operators valuable insights into the vehicle's and driver's quality and performance. Specifically, when dealing with perishable goods, unless alternative measures are taken to ensure proper temperature control during transport, the shipper is required to communicate to the service provider and, if necessary, to the parties responsible for loading and unloading the cargo the designated operating temperature for transportation [8]. A single notification suffices unless there are certain changes, such as shipment conditions necessitating a temperature adjustment. Carriers are expected to prove that the stipulated temperature conditions have been adhered to, although this demonstration might not be required for every shipment. Several effective methods exist to guarantee temperature control, ranging from the use of thermometers to temperature-measuring and recording devices. The shipper must specify the temperature for transporting products, encompassing both upper and lower temperature limits utilized to define the desired temperature zone. Additionally, minimum and maximum safety zones for the product must be included. If these limits are surpassed, corrective measures must be outlined to prevent further or recurring damage to the products, along with potential procedures for handling damaged goods [8]. In cases where the transportation route involves unloading, reloading, or storage at a distribution center, vigilant attention is given to monitoring temperature, maintaining cleanliness, and ensuring the safety of all transit storage facilities [9].

The benefits of innovations in the cold chain extend beyond profitability. Numerous significant advantages are associated with temperature control. Monitoring allows timely intervention, whether in the delivery through cold chains or in inspecting and repackaging damaged goods. In a broader sense, users gain crucial insights for making informed business decisions, resulting in a better user experience and often increased profitability. New technologies not only enhance the user experience but also contribute to the reduction of food and medical waste through proper monitoring and swift interventions. This, in turn, safeguards the integrity of transporting and distributing perishable products, particularly in regions where this is pivotal [10]. Transport monitoring provides, alongside enhanced profitability, a decreased burden on the service provider regarding temperature regimes, strengthened trust between contractual parties, reduced fuel consumption, lower operational costs for the fleet (when logistic provider services are utilized), and diminished redelivery expenses. A crucial advantage of monitoring temperature conditions during transport is compliance with regulatory standards, whether they are national or international, such as the U.S. Food Safety Modernization Act (FSMA) and Good Distribution Practice for Pharmaceutical Products (European Directive 92/25/EEC) [11].

3 Transportation Means and Units Used for Goods Transportation in the Cold Chain

Regulating temperature conditions during the air, land, or water transportation of goods can be achieved through the employment of either active or passive shipping systems. Crucial components for executing temperature-controlled transport encompass both active and passive systems, within which products are placed during transit, along with monitoring devices employed to record and oversee temperature conditions within the aforementioned systems [12].

Active systems keep a temperature-controlled environment inside an insulated enclosure, like refrigeration units, cold storage facilities, temperature-regulated trucks, and air containers [6]. These systems use external propulsion or on-vehicle mechanisms that are powered by electricity or alternative fuel sources. These systems employ mechanical or electrical systems responsible for power supply, coupled with thermostatic control, ensuring sustained adherence to the desired temperature for transported goods. Secondary packaging components refer to packaging elements utilized to safeguard pharmaceutical products sensitive to temperature conditions, simultaneously bolstering or improving the overall performance of the complete packaging. This encompasses items such as retainers, secondary protective packaging, and devices designed for recording temperature data [6].

Passive systems are mechanisms designed to uphold a temperature-controlled environment within an insulated casing, with or without thermostat regulation. They achieve this by employing a limited quantity of refrigerants, such as chilled or frozen gel packs, dry ice, or other phase change materials (PCM) [6]. These transport systems stand out for their fundamental simplicity and remarkable cost-effectiveness. On the other hand, it was established that PCMs have great potential in cold chains [3]. Passive systems can be employed in conjunction with refrigerating agents like dry ice, gel packs (often tailored for specific temperature ranges), as well as certain products (such as frozen meat) with ample thermal mass to contribute significantly to temperature control, and so forth.

Vehicles under temperature control refer to those equipped with an isolated, thermostat-controlled cargo space designed to maintain a controlled temperature environment, preventing products from being exposed to excessively high or low temperatures during transportation. Temperature control during air or water transport can be achieved through the use of either active or passive systems [6]. For transport durations shorter than 3 hours, thermally insulated containers are commonly employed. In the case of longer journeys, gel or ice packs are utilized, while larger shipments rely on vehicles with integrated refrigeration systems. Broadly speaking, two types of vehicles are used in cold chain transport: temperature-controlled and temperature-modified refrigerated vehicles. The former category includes vans, trucks, and semi-trailers with an isolated, thermostat-controlled cargo space maintained within the specified temperature range using a dedicated cooling unit. Vans and small trucks typically feature cooling units directly powered by the engine, while larger vehicles and semi-trailers are equipped with independent diesel cooling units. All refrigerated vehicles should be fitted with an electronic temperature monitoring system and an event recording system [6].

On the other hand, temperature-modified vehicles resemble temperature-controlled vehicles, except that these vehicles autonomously regulate the temperature of the cargo space, either through heating or cooling. The transported goods are generally packed into a qualified passive delivery system to keep them within the designated temperature range. The controlled temperature environment within the vehicle serves to prolong the autonomy of the passive transport system and safeguard the product from extreme temperatures. It is crucial to avoid prolonged exposure of packages to refrigerator temperatures, as this poses a risk of freezing the contents. Ideally, all efforts should be made to prevent active and passive packaging from being exposed to temperatures below +15°C for pharmaceutical products. To ensure this, temperature-modified vehicles should be equipped with an electronic temperature monitoring system and an event recording system. The following Figure 1 illustrates the precise procedure for packing refrigerated vehicles, emphasizing the need to: position goods at least 45 cm away from side walls, 30 cm from the end wall, and 45 cm from the door; leave a minimum space of 45 cm to the ceiling; arrange packages to allow for air circulation around and through them; remove debris that may obstruct airflow [6].

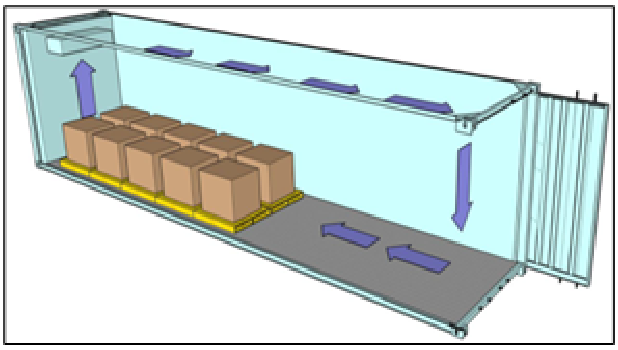

Figure 1. Guidelines for packing a refrigerated vehicle [6]

Figure 2. Mono-temp and bi-temp trailers [13]

A temperature-controlled trailer is defined as a cargo box affixed to a truck equipped with a control unit for actively cooling or heating the interior of the box. This control unit is sometimes referred to as a reefer unit. Certain types of these trailers have either a single control unit (referred to as a mono-temp trailer) or a control unit mounted at the front of the trailer with an evaporator at the rear (referred to as a bi-temp trailer). These represent the most prevalent road vehicles for maintaining controlled temperature conditions in both domestic and international road transportation within Europe, accommodating temperatures ranging from +2°C to +8°C and from +15°C to +25°C [13]. Bi-temp trailers enable the partitioning of cargo space into two temperature zones, facilitated by the evaporator controlling the temperature in the rear section of the trailer [13]. Figure 2 depicts both types, with arrows indicating the directions of airflow within the trailers.

A distinct advantage of passive systems in resource-constrained conditions is their reliable provision of secure transport for pharmaceutical products. They are also applicable for air transport. A properly qualified passive transport system can be employed to uphold effective temperature control of products within the cargo space during transportation. However, these systems should only be used after determining the route and container in which the products are packed, especially if containers are part of the process. Passive transport systems consist of a combination of insulated material and temperature-stabilizing media. When configured correctly, this combination can sustain the internal content of the packaging within a specified temperature range for a predefined transport period without relying on mechanical assistance. Packages are hermetically sealed in specific configurations, eliminating the need for continuous human or mechanical intervention to maintain a consistent temperature throughout transportation. However, they have a predetermined lifespan, and therefore, delivery must always be accomplished within the anticipated and predefined timeframe. The following Figure 3 illustrates an example of a reusable passive container and a single-use insulated carton [6].

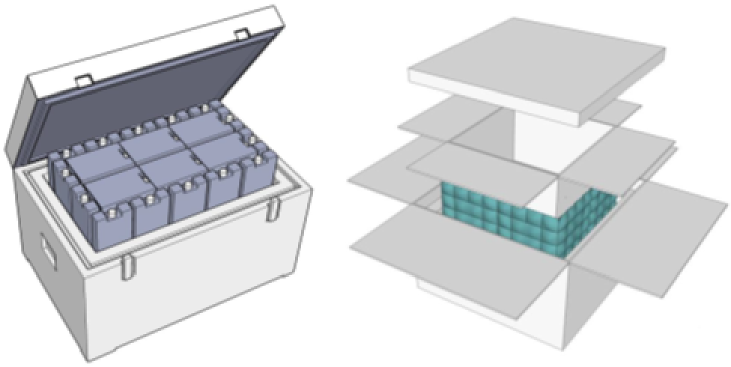

Figure 3. Reusable passive container and single-use insulated carton [6]

A typical active system in air transport is a purpose-built, portable container. These containers come in two types: exclusive cooling systems and systems with both heating and cooling capabilities. The temperature-stabilizing medium in active transport systems typically involves dry ice (for cooling only) or phase change materials (for both heating and cooling), serving as agents to control temperature. Additionally, compressor-based cooling systems are utilized. These containers are powered by batteries or rely on an external electrical source to operate compressors or heat pumps. Thermostatic control is utilized to activate the cooling or heating mechanism, and circulating fans contribute to maintaining the temperature within specific limits around the enclosed product. Figure 4 provides an illustration of one such container [6].

Figure 4. Active air transport container [14]

4 Devices for Monitoring and Tracking Temperature Conditions in Transportation

The primary rationale for employing temperature and humidity monitoring devices lies in the imperative for constant and real-time surveillance of temperature or humidity. This is essential to ascertaining whether the quality of temperature-sensitive products is jeopardized due to exposure to adverse or undesirable conditions. The selection of the monitoring device, as well as the type of technology (active or passive system), should be guided by user requirements [12]. Depending on the purpose outlined by user requirements, the chosen device may serve as a tool for approving or rejecting shipments or as an analytical instrument post-use, facilitating the identification of vulnerabilities in the transportation system, conducting trend analyses, or collecting performance data. The level of detail provided by the device varies significantly and is contingent upon the specific application and employed technology. This is a swiftly evolving technological domain. All monitoring systems must adhere to regulatory requirements and furnish evidence necessary to substantiate compliance with all conditions, thereby avoiding any compromise to the quality of pharmaceutical products sensitive to weather and temperature factors during transportation. When stipulated, the system must be capable of furnishing evidence of temperature variations essential for documentation purposes [12]. In cases where a temperature monitoring device is utilized during transportation, the shipper and service provider ought to collaborate on usage parameters, encompassing, but not limited to, the following aspects [8]:

•Data collection frequency;

•Permissible tolerances for temperature conditions;

•Methodology for data collection and transmission.

Devices for monitoring transport vehicles lack the capability to record the temperature status for each individual product or pallet. However, various indicators can be employed for this purpose, and these will be elaborated upon in the following sections. Single-use devices should be supplied with a manufacturer's calibration certificate that encompasses the entire temperature range for which the device is designed. These devices cannot be recalibrated post-use. On the other hand, reusable devices should undergo calibration against a certified and traceable reference standard at least once a year, unless specific justifications dictate otherwise. Calibration should guarantee the accuracy of the device throughout its designated temperature range. Regardless of the selected device, it is crucial to consider its specific features, including user-friendliness and seamless integration within the entire supply chain. Some devices may necessitate additional software or hardware, such as docking stations, which may not be acceptable in certain scenarios. Every device or system should exhibit precision, stability, reliability, and validation [12]. A risk assessment of the transport route is conducted to identify where temperature controls are necessary. Equipment utilized for monitoring temperature during transport in vehicles and/or containers is routinely maintained and calibrated at least once a year [9].

One method for transmitting, storing, archiving, and analyzing transportation data is through specialized short-range communication called DSRC (Dedicated Short Range Communication) [11]. Advancements in digital electronics have resulted in the creation of portable devices capable of recording temperatures. These devices are battery-powered and can be conveniently placed alongside or amidst temperature-sensitive products where it's necessary to monitor temperature or humidity. They can be configured to record data every second or at less frequent intervals, such as every hour. Some even allow for an 18-hour interval. The only limitation lies in the amount of data that can be stored; thus, if set for high-frequency recording, data will be overwritten earlier in the records. Temperature measurement accuracy typically stands at ± 0.5℃ and humidity at ± 3.0% RH (relative humidity). They can be programmed to commence recording after a specific delay period. A connection to a computer enables data transfer to Excel or any other analysis program. Alarms can be configured to trigger LED indicators if maximum or minimum thresholds are exceeded, promptly indicating a detected issue. The available types of devices on the market will be explained in detail in the next section of the paper.

Some advanced electronic devices also enable the collection of humidity data. However, it is generally considered that exposing products to humidity has a minimal negative impact on pharmaceuticals when they are sealed within primary packaging in a closed active or passive system. The accuracy and performance level of these devices vary depending on the manufacturer, so careful consideration is necessary in their selection to meet specific user requirements. Different devices generate diverse types and volumes of information. Devices like electronic data logging monitors can retrieve time and temperature records for the purpose of generating information in compliance with relevant regulatory requirements for documented data storage. In most cases, downloaded time and temperature data should be stored for a minimum of three years in an unchanged format that facilitates data retrieval. Suitable formats include printed hard copies or unaltered and renewable electronic media, such as computer hard drives, tape drives, flash drives, or DVDs. Storage in the form of secure web data may also be an acceptable solution [12].

If feasible, temperature monitoring systems should incorporate an alarm function. Some systems are designed to promptly alert relevant personnel to any changes in temperature conditions, allowing for a sufficiently extended period for proactive intervention to prevent exceeding upper or lower temperature limits. Moreover, it is essential to configure the alarm not to activate when the vehicle doors are opened, necessitating the definition of critical thresholds triggering the alarm [15]. Certain electronic sensors, beyond real-time temperature monitoring, provide drivers with insights into the cargo area's temperature regime. Specifically, a light on the monitor visible to the driver from the side mirror indicates whether the temperature is within the defined range [16].

4.1 Chemical Indicators (CIs), Chemical Time and Temperature Indicators (CTTIs)

Cis, also known as markers or phase change indicators, are usually embedded in cardboard substrates (Figure 5). These indicators rely on a phase change or chemical reaction occurring as a function of temperature. Examples of these devices include liquid crystals, waxes, polymers, etc. that undergo a phase change, altering their appearance depending on the temperature. Temperature threshold indicators are typically single-use devices, emitting a signal only when exposed to temperatures exceeding (rising indicator) or falling below (falling indicator) a predefined temperature threshold. They usually employ liquid diffusion to signal the exceeding of a time-temperature threshold for a specific event by irreversibly changing color, either instantly or with a certain time delay. The active colloid substance in these indicators typically consists of particles of material evenly dispersed in the liquid. At a certain relative temperature, particles in the colloidal liquid become unstable, eliminating the repulsive forces that keep the particles separate. Chemicals coagulate, leading to a change in color. The accuracy and precision of these indicators depend, to some extent, on human interpretation [6].

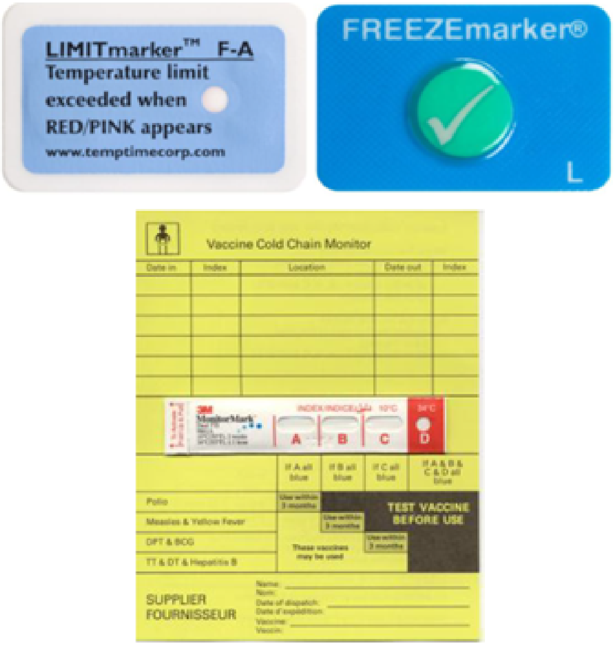

Figure 5. Different types of CIs [6]

CTTIs are typically chemically impregnated onto a pulp or cardboard substrate (Figure 6). Their diffusion process is utilized to assess the temperature conditions over time. Thus, CTTIs provide a measure of accumulated heat and not the current temperature. Once a color change occurs, reactions are generally irreversible, and exposure to low temperatures will not revert the indicator to its original state. The accuracy and precision of these indicators depend, to some extent, on human interpretation. They change color in response to cumulative temperature changes, such as heat. CTTIs accumulate under all temperature conditions in which the attached product is placed [6].

Figure 6. Different types of CTTIs [12]

A temperature-time indicator is defined as a device used to display a measurable, time-temperature-dependent change, enabling the monitoring of the complete or partial temperature history of a product (typically food) to which it is attached. Temperature-time indicators designed for monitoring partial temperature history respond only when the temperature surpasses a permissible threshold that is sufficient to induce a change in the product's quality or compromise its safety. On the other hand, indicators allowing the monitoring of the complete temperature history respond throughout the entire transit of the product. The activation of temperature-time indicators should be straightforward and, based on the activation method, they are categorized into two groups. The first group consists of indicators that become active immediately after production, activated by the manufacturer. Such indicators must be transported and stored at a specific temperature to prevent any alteration in the indicator's state prior to its application. The second group of indicators includes those activated subsequently, usually during application to the packaging itself.

4.2 Electronic Temperature Integrator (ETI)

The ETI is a portable device designed to measure temperature over time using its built-in sensor (Figure 7). They consist of four fundamental components: a thermistor sensor, a microprocessor, a memory chip, and a power source. Thermistors are thermally sensitive semiconductors whose resistance changes with temperature. They provide either a single temperature threshold or multiple alarm thresholds. These devices are utilized when making decisions about accepting or rejecting products, and their accuracy in terms of time and temperature is quite precise [6].

Figure 7. Different types of ETIs [12]

4.3 Electronic Data Logging Monitor (EDLM)

The EDLM is a compact, portable measuring device that records and stores temperature at predefined intervals using an integrated sensor, with programmable alarm capabilities [6]. These monitors, or temperature data loggers, are specifically designed for monitoring temperature conditions within containers. In recent times, they have found application in ensuring the stability of medicines during distribution. Data loggers serve as an ideal solution when there is a need for electronic recording of temperature or both temperature and humidity in an economical and efficient manner. The collected data is transferred to a computer via a USB port, where it undergoes analysis and is stored. They contribute to the security of the cold chain for medicines by capturing temperature and/or humidity data during transportation (Figure 8).

Figure 8. Different types of EDLMs [12]

4.4 Electronic Data Integrators (EDI)

The EDI is a hybrid electronic instrument programmed as an ETI with the capability for reporting and data generation, along with increased flexibility in data management. It utilizes a pre-programmed temperature threshold for post-analysis, usually carried out by trained personnel [6] (Figure 9).

4.5 Electronic Temperature Monitoring and Event Logger Systems (TMEL)

The electronic temperature monitoring and event logging system represent a system for tracking and reporting on air and/or product temperature, with the ability to record and report on cargo door openings, defrosting, and activate alarms. The advantage of these systems lies in their capability for remote monitoring through satellite connections [6] (Figure 10).

Figure 9. Different types of EDIs [12]

Figure 10. Type of TMEL [12]

5 Devices for Monitoring and Tracking Temperature Conditions in Warehouse

The complexity of monitoring temperature conditions in storage facilities depends on the type of goods being stored. The space where the goods are stored imposes various requirements that must be met, but the fundamental condition for temperature control involves the use of a thermometer measuring both maximum and minimum temperatures. The monitoring system should also have the capability to report any deviations from the allowed temperature range. Additionally, during storage, it is essential to provide adequate space between the goods and the internal surfaces of the storage unit to facilitate proper air circulation. The extent of temperature monitoring for goods requiring storage in ambient conditions depends on the size of the facility. The minimum requirement is to strategically place a thermometer and regularly read, record, and reset it, at least once a week. During periods of exceptionally hot or cold weather, the monitoring frequency should be increased. For large warehouses, continuous temperature recording is recommended. Temperature monitoring systems and devices should be installed in all facilities with temperature control, including cold storage rooms, refrigerators, and freezers used for storing goods. Sensors should be placed in areas where the greatest temperature variability is expected and positioned to minimize the impact of transient events, such as door openings. A comprehensive temperature monitoring system for temperature-sensitive products should be designed to record temperature and relative humidity for all storage areas where these products are stored or temporarily held. The system should cover zones such as storage, packing space, loading, handling of goods, etc. [17].

For the monitoring of temperature conditions, RFID technology stands out as an effective solution, facilitating paperless tracking operations. Beyond simply tracking changes in conditions, RFID improves operational efficiency and precision, reduces losses in logistics, and shortens storage times [18, 19]. The structure of such a monitoring system comprises RFID tags equipped with temperature sensors placed at fixed locations, aligning with both the stored goods and fixed readers. Additionally, it involves handheld terminals and a real-time data analysis software system [18]. Another prevalent technology in use today is data logger technology. Data loggers exhibit high accuracy and can track and measure slight temperature changes, even in challenging-to-access locations within storage facilities. Loggers can be easily repositioned to different locations or various areas that require monitoring [19, 20]. In addition to these technologies, alternative solutions for monitoring temerature in cold storages and freezing spaces include: thermometers, central temperature monitoring (CTM) systems, electronic temperature recorders (ETR), freezing indicators, IoT (Internet of Things) devices, wireless sensor networks (WSN), etc. (Figure 11) [21, 22].

When monitoring the temperature in a storage facility, the use of alarms is a viable option. The alarm must be triggered before the temperature falls below a specified level. What is crucial when using alarm systems, besides notifying of undesirable changes in temperature conditions, is the prevention of activation during transient changes in temperature conditions, such as door openings and similar scenarios. When considering warehouse mapping, data loggers play a pivotal role. They offer a comprehensive overview of the storage environment, facilitating easy analysis to determine whether the warehouse maintains safe conditions for the stored product. Some guidelines that company needs to implement for successful temperature monitoring in warehouses are outlined below [23].

Figure 11. Devices for temperature monitoring in warehouse [17, 24]

Step 1: Creating a validation plan – a document that delineates the actions required to ensure compliance with standards.

Step 2: Identifying areas to be monitored and areas of risk - as each warehouse is unique, it is essential to gather fundamental information about a specific environment before commencing the mapping process. Factors to consider include the spatial scope, positions of air conditioning and space heaters, the arrangement of equipment within the space for optimal airflow, high-traffic areas such as windows and doors, as well as loading areas for goods (Figure 12).

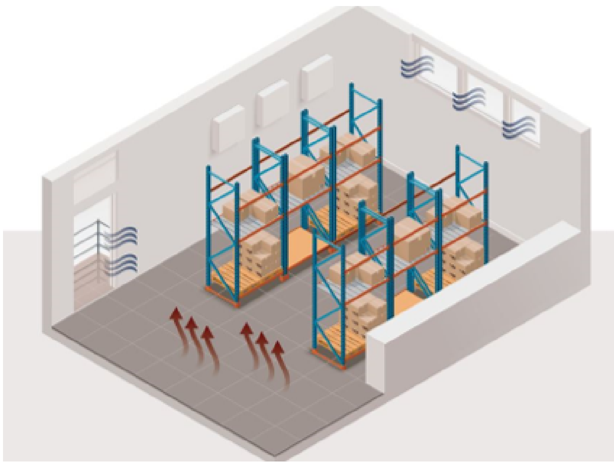

Figure 12. Different warehousing factors [23]

Step 3: Development of a comprehensive protocol - utilizing information gathered during risk assessment, it is imperative to create a detailed protocol pertaining to mapping. Some key considerations include defining which parameters will be monitored and at what intervals, determining the quantity and locations of data loggers, creating a facility layout illustrating the placement of each data logger, specifying the duration of the mapping process, and addressing other relevant factors.

Step 4: Selection of suitable equipment - when selecting equipment, it is essential to ensure that the chosen tools have minimal potential for data loss or errors. Additionally, the equipment should demonstrate high precision for each parameter, rapid response time, device sensitivity, and other pertinent criteria.

Step 5: Deployment of data loggers in the warehouse - data loggers should be strategically positioned throughout the entire warehouse (Figure 13).

Step 6: Conducting tests and reviewing results - the findings from the mapping tests should encompass information such as the date and time of testing, data for each device, and details regarding the monitored parameters (including minimum, maximum, and average values). It is also essential to provide graphical representations of all data throughout the testing period, information on reading speed, and similar details. This is crucial for the timely identification of any irregularities, enabling corrective actions to be taken to ensure proper and satisfactory working conditions.

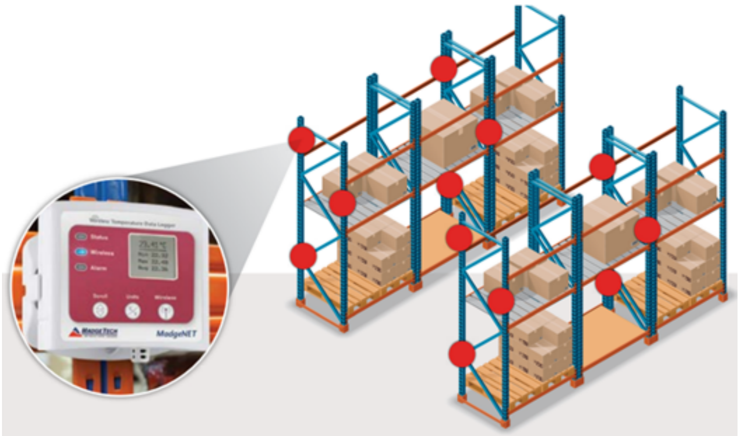

Figure 13. Data loggers for temperature monitoring in warehouse [23]

Step 7: Defining necessary modifications - common modifications often involve adjusting the locations of mobile racks situated too close to risk factors, repositioning ventilation openings, rearranging shelves to prevent airflow obstruction, incorporating additional fans or enhancing ventilation in specific areas, blocking sunlight that may create a warm zone, and making other relevant adjustments.

Step 8: Execute the mapping process.

6 Discussion and Trends

Based on everything mentioned, theoretical and managerial implications can be identified. Theoretical implications and contributions primarily involve addressing the gap related to the evident lack of frameworks for temperature monitoring in the cold chain. Furthermore, numerous areas have been opened up for potential future research, which will be further discussed in the conclusion. On the other hand, for practitioners and other stakeholders, this paper offers a quick introduction to all the significant elements of temperature monitoring in the cold chain. In this way, practitioners can make reliable and prompt decisions.

The paramount innovations in the cold chain are specifically associated with the monitoring and surveillance of vehicle temperature conditions, employing remote sensors to mitigate the wastage of products falling below acceptable quality standards. Sensors, as devices facilitating the observation of temperature ranges, are adaptable to the specific requirements of the transported goods. Although the majority of innovations are directed towards the air transport sector, there is a discernible increase in innovative solutions within ocean transport as well [10].

Logistics providers like DHL, FedEx, UPS, Kuehne + Nagel, and DB Schenker offer solutions that leverage GPS or RFID-based sensors for real-time tracking and monitoring of temperature and humidity levels during transportation. These systems also enable web-based real-time tracking, including report generation. A notable example is FedEx's SenseAware [25]. This multimodal solution allows for the tracking of location, temperature, light exposure, relative humidity, pressure, etc. Through these services, the SenseAware system provides comprehensive insights into the actual conditions of the transported products.

DHL's solution for temperature control stands as another notable innovation. In 2013, the company introduced DHL Thermonet, an RFID-based air transport service that enables customers to monitor the temperature of their goods throughout the delivery process [26]. The complexity of organizing air transportation in the cold chain has been confirmed in the research [27]. Additionally, DHL implemented Ocean Secure technology for ocean transport. Ocean Secure grants users' real-time access to temperature data at any given point and facilitates corrective actions if needed [28].

Modern refrigerated trucks, commonly referred to as reefers, are designed with high adaptability, allowing them to be configured within minutes for the transportation of various products. Many trucks can accommodate products with diverse temperature requirements by adjusting the internal cargo compartments. Modern trucks often feature GPS tracking systems that provide location data, assisting operators in maintaining temperature control in specific sections. Over the past decade, the use of data loggers for temperature monitoring during transportation has become increasingly prevalent. While real-time monitoring has made significant strides, shippers are now capable of demonstrating product quality for customs clearance [5].

In addition to measuring temperature during transportation, monitoring temperature during storage is equally crucial, particularly for products that necessitate specific temperature conditions. The warehousing sector is experiencing notable trends, including efforts to stabilize stock levels post-COVID pandemic, the integration and utilization of artificial intelligence (AI) in cold storage, the introduction of automation in warehousing, and the implementation of the IoT, among others [29, 30].

According to a market analysis report by Grand view research, the global frozen food market (covering fruits and vegetables, potatoes, meat, ready meals, and fish and seafood) is projected to grow at a compound annual growth rate (CAGR) of 5.2% from 2022 to 2030. This anticipated expansion is expected to create challenges in the cold chain transportation flow, especially in urban overpopulated areas, impacting cold storage facilities. The cost and availability issues of commodities like steel and lumber, essential for storage construction, due to ongoing supply chain challenges will further hinder the renewal of existing cold storage facilities and the construction of new ones. Investments in software for enhanced visibility across the entire supply chain, especially for refrigerated products, are anticipated in 2024. Real-time monitoring with GPS-enabled devices and the potential use of artificial intelligence will play a crucial role in improving efficiency, safety, and traceability. The pharmaceutical industry is expected to experience growth due to globalization, an aging population, and health issues related to advanced age. Increased demand for innovative medicines and biopharma products, coupled with the rising global middle class with higher disposable incomes, will contribute to investments and innovation in the pharmaceutical sector. Also, automation will be a key focus in cold chain logistics in the coming year. Companies will invest in optimizing processes, utilizing data more effectively, and increasing scalability. Automation and robotic solutions will address labor shortages, particularly in cold storage, leading to improved efficiency and waste reduction. The energy-intensive nature of the cold chain industry emphasizes the need for a transition to renewable energy sources, such as solar power. Sustainability strategies, including the phasing out of energy-inefficient infrastructure, will be crucial for cold chain players to demonstrate their commitment to the energy transition. Cold chain businesses and providers are expected to invest more in the packaging and storage of fresh food, developing facilities to keep fresh produce closer to its final destination. Finally, collaboration between food-producing companies and fully integrated supply chain providers will continue to increase. The cold chain market will seek more integration to add value, minimize handovers, and reduce waste in their operations. Strategic alliances and partnerships will be formed to enhance efficiency, visibility, and sustainability in the coming year [31]. This becomes even more intricate when considering that distribution can be executed via various distribution channels [32] and that risks in cold storage are inevitably present [33].

7 Conclusions

Efficiently transporting a shipment necessitates time and coordination, and any delay can have adverse consequences, particularly if the cargo is perishable. To ensure the secure transport of products, companies in the pharmaceutical, medical, and food industries are increasingly depending on the cold chain. Monitoring within the cold chain is a pivotal element responsible for providing straightforward evidence of accountability, temperature conditions during transport, and other logistical activities. The benefits of monitoring are manifold, and the investments are substantial. However, as mentioned earlier, the costs of redelivery due to poor product quality are considerably higher. Therefore, it is anticipated that monitoring will be even more widely adopted and will become an even more integral part of the cold chain.

Transportation is under temperature control, and the cold chain is experiencing global growth to meet the escalating demands of technological advancements and globalization. Nevertheless, the significance of these innovations would be undermined if not for the existence of cold chain logistics and temperature-controlled transport that sustain perishable products in optimal conditions throughout the entire supply chain for a specific product. In developing nations, the advent of the cold chain offers diverse opportunities, such as introducing products from small and medium-sized farmers and businesses that, thanks to the cold chain, now have the chance to operate in the international market. Furthermore, cold chains grant consumers access to products that were previously unavailable to them locally. The expansion of the cold chain stands as one of the most significant challenges for businesses in any international market. Developing markets lack the infrastructure required to support cold chains. There are added costs and complications due to the absence of reliable power for refrigeration, connections for refrigerated containers equipped with their own cooling system at ports and transportation hubs, and ensuring adequate facilities at the final location, i.e., with clients. Globalization has diminished the relative distance between world regions. However, cargo can be easily damaged during transportation operations, precisely due to the increasing physical separation between the seller and the buyer. Some products may suffer damage due to temperature shocks (significant temperature differences), while certain product types may be adversely affected by minor temperature variations. For a variety of products designated as perishable goods, especially food products, quality degrades over time due to chemical reactions, which can largely be mitigated with lower temperature conditions.

The sole limitation of this study lies in the isolated examination of the transportation process, excluding the consideration of other activities such as reception, dispatch, etc. This study opens up numerous directions for future research. Subsequent papers should address decisions regarding the selection of suitable solutions and devices, with a substantial portion of the criteria and alternatives outlined in this study. Furthermore, it is crucial to evaluate the risks that emerge within the cold chain. Attention should also be directed towards other facets of the cold chain, including handling, storage, etc. A comprehensive understanding and the ability to make appropriate decisions in the cold chain can only be attained by considering all its activities.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Confilict of Interest

The authors declare that they have no conflicts of interest.

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