

18. The cold chain as a resilience feature of the supply chain

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Abstract: Cold-chain technologies are discussed as a practical source of resilience for temperature-sensitive supply chains. The chapter reviews literature on supply-chain resilience, sustainable supply-chain management, cold-chain applications and international rules governing food and pharmaceutical logistics. Cold chains preserve product integrity, reduce spoilage, limit waste, support vaccine and medicine quality, enable global distribution and help firms adapt to climate-related and operational disruptions. Regulatory compliance is central, with standards such as ATP, ISO 22000, ISO 23412, Good Distribution Practices and IATA temperature-control rules shaping transport and storage. The chapter also notes drawbacks: high energy use, infrastructure costs, monitoring demands and environmental burdens from refrigerants. Resilience improves when cold-chain systems are paired with energy efficiency, natural refrigerants, renewable power, traceability and waste-reduction strategies.

Keywords: supply chain resilience, cold-chain technologies, global supply chain, sustainability, regulatory compliance.

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Introduction

Global supply chains are increasingly exposed to geopolitical tensions, climate-related events, infrastructure failures, and operational disruptions. These challenges are particularly significant for temperature-sensitive products, whose quality and safety depend on uninterrupted storage and transportation under controlled conditions. Against this background, cold-chain technologies can be viewed not only as a means of product preservation but also as an important source of supply-chain resilience and sustainability. This chapter examines the relationship between cold-chain management, resilience, sustainable supply-chain practices, and regulatory compliance, while also considering the environmental and operational challenges associated with temperature-controlled logistics.

18.1. Supply chain resilience

Resilience can be defined as ‘an ability to recover from or adjust easily to misfortune or change’ (*Merriam-Webster dictionary*, 2025) or ‘the capacity to withstand or recover quickly from difficulties, toughness’ (*Oxford dictionary*, 2025). These two terms best reflect resilience in the context of business and management. In relation to supply chains, resilience takes on an additional dimension, which indicates the difficulty in building resilience and maintaining it over time. The supply chain as a network of cooperating companies (Christopher, 1998), the purpose of which is to deliver finished goods to the market (Quinn, 1997), is a complex structure. Supply chains can be treated as super-organisations (Ballou, 1992), complex organisational systems (Roh et al., 2017), and business ecosystems (Bechtel & Jayaram, 1997). A resilient supply chain is only as resilient as its weakest link, meaning that all of its components are equally resilient, despite each having a different scope of operation, different characteristics, different features, and different capabilities. This is where the role of the leading company in the supply chain, the leader, is fully revealed. This leader should manage the resilience of the entire supply chain – adopt the position of the architect of resilience, set standards, and support their implementation. The key is the introduction of unilateral, broad and multi-threaded cooperation in the supply chain, which is based on reliable resources and process foundations, clearly defined goals and solid commitment and mutual obligation (Coleman, 2012).

Loss of resilience does not necessarily mean disruption to the supply chain or its complete inability to act. Loss of supply chain resilience should be understood through the effects of its operation, i.e. the value delivered to the end

customer, or otherwise the level of customer service. Loss of the previous ability to operate may be expressed in incomplete deliveries or extended delivery lead times. At the same time, it should be noted that the supply chain may not only be unable to deliver value and serve customers at the previous level, but may even cause losses on the recipient's side, which in the quantitative sense can be treated as delivering negative value (World Economic Forum, 2013). Resilience is therefore a complex category.

The idea of resilient supply chains naturally draws from the concept of organisational resilience, which is based on five pillars: leadership, organisational culture, people, systems, and workstation organisation (Bell, 2002). Another set of pillars of a resilient supply chain is included by Wilding (2013). In his model of a resilient supply chain, Wilding considers close cooperation, supply chain engineering, risk management, and agile management as very essential elements.

Resilience can be assessed from both a reactive and proactive perspective. In the reactive approach, rebuilding the potential of the supply chain after a crisis situation allows it to achieve a higher level of resilience, shifting it to a more stable equilibrium (Christopher & Peck, 2004; Sheffi, 2005). The proactive approach, on the other hand, involves bolstering supply chain resilience in a way matching the anticipated future threats; here, the level of resilience directly depends on the accuracy or quality of forecasts, which may only be verified when a crisis situation occurs. Signs of supply chain resilience include the ability to weaken internal and external factors that cause disruptions, as well as the ability to prevent the transmission of disruptions along the supply chain. This issue is crucial for analysing their resilience, and many studies are required to elaborate with precision the methods and directions of disruption transmission, and then to control it in an organised way. This is currently a vital research thread in supply chain management, and is currently the subject of several studies, including Świerczek's pioneering work (2012). Other scientific research studies the behaviour of supply chains in the wake of various disasters (disaster supply chains) have already provided a substantial empirical data. The scientific studies within this research stream include seminal works for developing comprehensive theoretical foundations in disaster supply chain management, such as Hale & Moberg (2005), Ergun et al. (2010), Dash et al. (2013), Pfeiffer et al. (2017), Ateş (2023), and Ojo (2024).

Currently, increasing resilience can be classified as one of the most important directions of the evolution of supply chains (Szymczak, 2015), especially those which have already achieved satisfactory results in other aspects of functioning. There, resilience is now embedded into many business strategies, the main rationale being events that disrupt the operations of businesses. Many such events have occurred in recent years, especially sudden and unpredictable ones, such as

the global financial crisis (2007–2008), Fukushima tsunami (2012), Brexit (2020), worldwide COVID-19 pandemic (2020), and Russia's invasion of Ukraine (2022). These shocks inflicted both an economic impact on supply chains, forcing them to function in completely different business realities overnight, and a physical impacts which abruptly paralysed operations. Only very few supply chains managed to cope with these threats, implementing various solutions to survive and strengthen themselves for the future.

Beyond geopolitical and macroeconomic shocks, the imperative to boost supply-chain resilience is also propelled by 'disruptive technologies' and rapid technological advancement described as Industry 4.0. This increases the interest in resilience in two ways. Firstly, supply chains want to be prepared for upcoming changes in the way industries and markets operate, and secondly, they want to implement these technologies to increase their resilience to unforeseen events. Technologies such as artificial intelligence (AI), machine learning (ML), block-chain and digital twins can enhance supply chain resilience.

Cold-chain technology is equally important for increasing the resilience of the supply chain, specifically its ability to deliver temperature-sensitive goods without compromising their quality and suitability for use. This applies to all perishable goods, fresh agricultural products, seafood, frozen foodstuffs, some chemicals and pharmaceuticals, photographic films – collectively referred to as 'cool cargo'. The cold chain must provide an uninterrupted sequence of refrigerated supply, production and distribution activities including transport and storage to maintain the safety of materials, production in progress, and finished products. At the same time, this minimise losses and waste.

18.2. Sustainable supply chain management

While sustainability has certainly been a business and management buzzword for many years, its interpretation varies across different industries and areas of management. However, making the supply chain sustainable is certainly an effect of appropriate management efforts, which gave rise to the concept of supply chain management. Sustainable supply chain management involves a firm's strategic efforts to achieve social, environmental, and economic goals through the systematic coordination of buyer-supplier relationships and inter-organisational business processes (Carter & Jennings, 2002). According to IBM (2025), the scope of managing sustainable supply chain – both objective and subjective – is crucial, as sustainable supply chain management involves integrating environmental, social and financial considerations into the sourcing, production and distribution of goods and services. The practice involves the entire supply

chain, all participants, entire lifecycles of products and services. Sustainability is perceived in its three dimensions, and has three pillars: social, environmental, and economic (Purvis et al., 2019). This is why supply chain sustainability encompasses aspects like improving working conditions, social risk reduction, promoting diversity, implementing anti-corruption policy, respect for human rights, reducing greenhouse gas emissions, conserving and recovering energy, saving water, recycling materials, moving away from single-use packaging, contributing to long-term economic development of nations and supporting well-being of future generations.

Evidently, a sustainable supply chain goes beyond the 'green supply chain' concept discussed since the mid1990s. To express a holistic approach to sustainability within supply chains, the term 'white supply chain' was coined. Suktanachananun et al. (2024) developed a model of white supply chain in the food industry. Their White Supply Chain Management (WSCM) approach integrates three key components: Green Supply Chain Management (GSCM), Corporate Supply Chain Management (CSCM), and Ethical Supply Chain Management (ESCM). These components, when combined, create a universal approach to sustainability that encompasses environmental, social, and ethical considerations.

The white supply chain approach seems to be appropriate for analysing cold chains particularly as many issues specific to the cold chain are relevant within the scope of GSCM. One issue is the adoption of ecological refrigerants, such as chilled water (refrigerant R-718), ammonia (refrigerant R-717), and hydrocarbons (refrigerants: R600a – isobutane, R290 – propane, R1270 – propylene), as well as natural components of the atmosphere, such as air (refrigerant R-729) and carbon dioxide (refrigerant R-744). These alternatives all have favourable physical parameters, good thermodynamic properties, high chemical stability and excellent cooling efficiency, in addition to being safe for humans and the environment. It is therefore important for all parties in the cold chain to decisively and systematically move away from harmful synthetic refrigerants.

The second important issue is the reduction of atmospheric emissions of freons (CFCs – chlorofluorocarbons), fluoro compounds derived from methane and ethane which are used in compressors of refrigeration devices. Studies have shown that freon molecules do not disintegrate and remain in the atmosphere for up to 100 years, contributing to ozone depletion, i.e. the lowering the amount of ozone (O₃) in the Earth's atmosphere, mainly in the polar regions (Crutzen, 1970; Molina & Rowland, 1974). This permits increased amounts of ultraviolet radiation to reach the Earth, which is harmful to living organisms. Freons have been mostly replaced in refrigeration by hydrochlorofluorocarbons (HCFCs), e.g., the popular R134 refrigerant, which despite being greenhouse gases, have a much smaller impact on ozone destruction.

While the challenges facing CSCM and ESCM in cold chains mirror general issues typical for all supply chains, specific and detailed issues related to the organisation of materials flow at a controlled temperature can be distinguished here. Within the scope of CSCM, a key challenge is ensuring cooling efficiency (in storage and transport) in the international cold chain, which runs through different climate zones. This necessitates the careful selection of logistics service providers and transport companies possessing the appropriate refrigeration equipment. Another issue is the safety of the products being moved in terms of the risk of contamination and poisoning (such as potential terrorist attacks). Managing these challenges will foster relations with stakeholders, while at the same time promoting good supply chain practices. Within the scope of ESCM, particular attention should be given to securing and, if possible, using products for which the cold chain has been broken at a given stage of the flow, thereby preventing them from being traded.

18.3. Regulations influencing the cold chain

Due to the international scope and complexity of operations within the global supply chain, there is no single, universal set of regulations governing the technologies used in the cold chain. Instead, depending on the specific application and region, regulations from various regulatory bodies apply. One differentiating factor is the industry, particularly pharmaceuticals and food. Another factor could be the branch of transport to which the regulations apply.

In the case of pharmaceuticals, the U.S. Food and Drug Administration (FDA) has established regulations (CFR 21 Part 211) for the storage and transportation of drugs, with requirements related to temperature control. Similar regulations are enforced in other countries by national health agencies. Regarding food, most countries have regulations established by national or regional food safety agencies covering the storage and transportation of food. These regulations focus on maintaining appropriate temperatures for different types of food to prevent spoilage or the development of pathogens (Stern Review, 2006).

Regulatory scope is another differentiating factor, with regulations setting limits in areas such as temperature, data monitoring, equipment, and packaging. In terms of temperature control, regulations may specify the required temperature ranges for different products during storage and transportation. In some countries, data monitoring is mandatory and involves recording and storing temperature data throughout the cold chain to ensure compliance with the regulations. Furthermore, regulations may require qualification and validation of equipment used in the cold chain (e.g., refrigerated vehicles, freezers) as well

as packaging materials (e.g., insulated containers) to ensure compliance with specific performance standards.

Despite variations in the geographic scope of logistics operations, certain regulatory bodies set the standards for the industry. These include national health agencies, such as the FDA in the United States, industry organisations related to pharmaceuticals, food, or cold-chain logistics, and international organisations, such as ISO (International Organization for Standardization).

Technologies used in the cold chain must comply with specific international standards and regulations that ensure the safety of transportation and storage. The most significant of these are: the Agreement on the International Carriage of Perishable Foodstuffs (ATP), which outlines the requirements for transportation vehicles carrying perishable food items; ISO 22000, the international standard for food safety management, which also covers temperature control in the cold chain; Hazard Analysis and Critical Control Points (HACCP), a system used to identify hazards and critical control points to ensure food safety; the ISO 23412 standard, which pertains to the last mile delivery of refrigerated goods, covering temperature and insulation regulations; and Good Distribution Practice (GDP) for pharmaceuticals, which governs temperature control during the transportation of medicines and vaccines.

The ATP Convention plays a key role in ensuring proper temperature control within the supply chain of perishable food products. It was drafted in Geneva in September 1970 and covers various aspects, including transportation conditions (e.g., for raw meat, fish, milk), technical requirements for transport vehicles, certificates, and distinguishing marks for vehicles carrying these products. Perishable goods include the following categories: plant-based food, animal-derived products, products obtained through the refinement of plant or animal materials, and live plants. Its regulations aim to optimise vehicles for transporting such items, which is crucial for safeguarding public health.

The ATP Convention plays a pivotal role in controlling temperatures within the supply chain of food when specific transportation conditions are required (Aditjandra et al., 2025). It establishes standards for isothermal transport vehicles, refrigerators, freezers, and heated vehicles, minimising the risk of disruptions in the cold chain. The provisions of the agreement ensure the use of appropriate technologies, such as refrigeration units and thermal insulation, allowing food products to maintain quality and health safety at every stage of transportation. In the context of the cold chain, ATP not only provides clear standards for vehicles and containers transporting food that requires controlled temperatures, but also regulates the mandatory use of technologies such as refrigeration units and thermal insulation, minimising the risk of disruption to the cold chain.

Although the ATP Convention regulates temperature-controlled transportation, it is not universally binding in an international context. It applies to signatory states that have ratified it, mainly in Europe but also in countries such as the USA, Kazakhstan, Morocco, the United Kingdom, and the Russian Federation. While it is binding for international road and rail transport, many countries also apply its provisions to domestic transportation.

The ISO 22000 standard does not provide specific guidelines for managing the cold chain but focuses on establishing a Food Safety Management System (FSMS) that encompasses all aspects of food safety, including temperature control. Therefore, ISO 22000 can be used to develop a cold-chain management plan that meets specific needs and complies with other relevant regulations.

By incorporating the following elements into the FSMS, the ISO 22000 standard helps effectively manage cold-chain processes, minimising the risk of food spoilage or contamination due to temperature fluctuations:

- Hazard Analysis and Critical Control Points (HACCP) – Identifying potential hazards throughout the food supply chain, including temperature control failures. In the context of the cold chain, this may include identifying critical control points (CCPs), such as receiving temperatures, storage conditions, and transportation conditions.
- Operational Prerequisite Programmes (PRP) – Programmes that establish basic food safety conditions, which can be tailored to cold-chain management. Examples of PRPs related to the cold chain include: procedures for the calibration and maintenance of temperature monitoring equipment, training for cold-chain personnel in proper temperature control procedures, documentation of temperature control procedures and monitoring logs, validation of cleaning and disinfecting procedures for cold-chain equipment (Gustavsson et al., 2011).

ISO 22000 does not specify exact temperature values but requires the establishment of appropriate temperature ranges based on the type of food and applicable regulations. The FSMS should also include procedures for monitoring temperatures at critical control points and maintaining compliance records. In the case of temperature deviations, corrective procedures should be implemented to minimise risks to food safety. Overall, the ISO 22000 standard provides a framework for managing food safety, including processes related to the cold chain. By implementing an FSMS that incorporates these principles, it is possible to ensure that cold-chain operations are in line with best practices and contribute to overall food safety.

ISO 23412, on the other hand, establishes international standards for logistics companies involved in refrigerated transportation, mandating the use of modern

temperature monitoring and control technologies. Through the application of refrigeration units, intelligent transportation management systems, and advanced insulation, stable temperature conditions can be maintained even during complex deliveries with multiple transshipment points. The implementation of this standard is crucial for enhancing the safety and quality of deliveries of sensitive products, minimising the risk of spoilage and economic loss. It defines requirements for providing temperature-controlled transportation services for shipments containing temperature-sensitive goods (including food) in road transport. It covers all stages of refrigerated delivery, from the acceptance of goods from the service user, through transfer between refrigerated vehicles or containers, to final delivery to the destination. The standard places significant emphasis on the application of modern refrigeration technologies. It not only outlines requirements for cooling systems in vehicles and containers (as in ATP) but also highlights the need for real-time temperature monitoring using temperature sensors, GPS systems with temperature logging functions, and IoT technologies. The use of automated routing and route optimisation systems is recommended to minimise transport times and the risk of temperature fluctuations due to long stops or inefficient planning. This standard also specifies procedures for the safe transfer of goods between refrigeration units, ensuring the continuity of the cold chain. The use of electronic tracking systems for shipments is also highlighted, allowing customers and logistics service providers to monitor the transport.

ISO 23412 has limited applicability. Firstly, it does not cover all branches of transport, and does not apply to air, sea, or rail transport. Secondly, it does not cover shipments with their own cooling system or direct refrigerated deliveries. Thirdly, the ISO 23412 standard does not provide guidelines for measuring the temperature of the shipment itself, but only sets requirements for the transport system, not the quality of goods before their pickup. Finally, the transport of pharmaceuticals and medical products is subject to separate regulations (ClassNK 2021).

In the context of cold chains, GDP plays a key role in ensuring the proper storage and transportation conditions for temperature-controlled products. Good Distribution Practice (GDP) constitutes a quality system that outlines the responsibilities and processes for managing the risks associated with the wholesale distribution of pharmaceutical products. It includes the organisational structure of companies, procedures, resources, and processes. Quality control systems in the pharmaceutical industry are crucial for ensuring the safety and high quality of medicinal products. Companies are required to continuously monitor processes such as the transport, distribution, storage, and sale of drugs, in accordance with both national and international regulations. Pharmaceutical

wholesalers must ensure the high quality of medicinal products. Consequently, warehouse owners must provide appropriate storage conditions, including maintaining cleanliness, controlling humidity, monitoring room temperatures, ensuring air circulation, and proper labelling. Distributors are also obligated to demonstrate the legality of drug sources and monitor the supply chain. GDP regulations apply to companies involved in the purchase, sale, storage, and transportation of drugs intended for human use, as well as veterinary drugs. The requirements also extend to the personnel of distribution companies. GDP regulations must be implemented by warehouse and pharmaceutical storage owners, and the quality of distribution is overseen by qualified staff.

GDP mandates that companies use appropriate refrigeration technologies, such as coolers and refrigeration units, for products requiring cooling and ensure continuous temperature monitoring throughout the supply chain. The warehouse owner must have a permit confirming compliance with health and safety and GDP standards. An important element is the monitoring of room temperatures, temperature mapping, and the installation of temperature sensors and data loggers. In this regard, automated temperature measurement systems help reduce the risk of losses and avoid financial penalties (Stajniak & Konecka, 2014).

An example of the practical application of regulations in cold chain supply is the International Air Transport Association's (IATA) Temperature Control Regulations (TCR), which address issues related to temperature management in air transport. Through collaboration with leading agencies and organisations, the IATA has significantly improved the preparation for transporting COVID-19 vaccines, which posed a major challenge in the context of refrigerated pharmaceutical supply chains (IATA, 2023).

18.4. Cold chain applications in sustainable supply chain

In the context of the modern, competitive market, establishing an effective cold supply chain that incorporates sustainable suppliers is essential. Manufacturers and suppliers of cold products are increasingly adopting sustainable practices and striving to adhere to recognised environmental standards. While the implementation of these practices requires both time and significant investment in infrastructure, the long-term benefits may include enhanced market appeal for both products and services (Chaabane et al., 2022). Suppliers of frozen food products, often located in remote regions, must integrate sustainable practices to ensure their products meet global acceptance and regulatory requirements (Kartoglu & Ames, 2022). The inherent characteristics of cold chain technologies (CCT) facilitate the achievement of this objective.

A primary goal in the application of cold-chain systems is the preservation of product integrity throughout the supply process. Within the context of transforming into a green supply chain (GSC), the utilisation of cold-chain technologies is one of priorities. CCTs are designed to maintain optimal temperature conditions, thereby preserving the quality and efficacy of temperature-sensitive products. This function underscores the environmentally beneficial aspect of cold-chain technologies, as they play a crucial role in safeguarding the integrity of such products throughout the supply chain. Cold-chain systems contribute significantly to reducing food spoilage by ensuring that appropriate temperatures are maintained during storage, transportation, and distribution (Gustavsson et al., 2011). The reduction in food waste subsequently decreases the environmental impact associated with food production, including lower water consumption, less land use, and fewer greenhouse gas emissions. Moreover, as Demirkiran et al. (2022) found, the adoption of proper cold-chain technologies enhances operational efficiency. Efficient cold-chain systems are capable of optimising energy consumption by maintaining precise temperature control without resorting to excessive cooling (Shishodia et al., 2021). This optimisation can be achieved through innovations such as insulated packaging, intelligent sensors, and route optimisation software, which together contribute to a reduced carbon footprint.

Global supply networks depend heavily on frequent and extensive transportation operations, which often place considerable strain on delicate food products. By regulating the temperature during transportation and storage, cold chain technologies (CCT) can reduce the reliance on chemical preservatives. These technologies have been shown to significantly minimize the need for preservatives in food products (Mercier et al., 2017). The maintenance of optimal temperatures inhibits microbial growth, which not only allows for more natural and potentially healthier food products but also reduces the environmental impact associated with the production and disposal of chemical preservatives. In addition, modern consumers are increasingly concerned with the types of preservatives used throughout the food supply chain. Therefore, the reduction of potentially harmful substances can provide a competitive marketing advantage (Novitasari et al., 2019).

Similar to the food industry, temperature-sensitive pharmaceuticals and vaccines are particularly vulnerable to degradation. Cold-chain technologies ensure the stability and efficacy of these products by preventing their deterioration. Given the often high cost of pharmaceuticals, the implementation of these technologies can help to reduce logistics and disposal costs. This, in turn, decreases the need for overproduction and the disposal of expired medications, thereby minimising resource consumption and mitigating the risk of environmental contamination. Cold-chain technologies (CCT) enable logistics operators

to mitigate economic risks and reduce the likelihood of spoilage and degradation, often resulting from supply chain disruptions. The advancement of cold-chain technologies increasingly incorporates environmentally sustainable practices. These practices include the use of recyclable or biodegradable packaging materials, the adoption of natural refrigerants with lower environmental impact, and the integration of renewable energy sources to power cold storage facilities (Evans, 2023). These strategies align with the principles of Green Supply Chain Management, as reflected in current industry practices and outlined in relevant recommendations.

One of the practical objectives of cold-chain management is to ensure compliance with regulatory requirements. During cross-border transportation operations, there is a heightened risk of encountering conflicting norms and regulations. Cold-chain practices help to maintain adherence to stringent regulatory standards governing the storage and transportation of temperature-sensitive goods. Achieving this goal involves three key components: temperature monitoring, documentation and traceability, and standard operating procedures. Temperature monitoring is essential for ensuring compliance and validated temperature sensors provide accurate data that aligns with regulatory requirements. Continuous temperature monitoring across the cold chain is also vital for maintaining compliance, which involves the deployment of data loggers, thermometers, and other monitoring systems to track and record temperatures throughout storage, transportation, and handling (ISO, 2024). In many cases, digitalisation of the supply chain is an important co-factor determining usage of CCT (Ramanathan, et al., 2022). For documentation and traceability, electronic data management systems, commonly used in supply chain management, facilitate efficient record-keeping and enhance compliance. Detailed records of temperature data, including timestamps and product identification, are crucial for demonstrating compliance during audits (Bremer, 2018). These records allow product movements to be tracked and any temperature deviations identified, thus reducing the risk of distributing spoiled goods. This is particularly important because food contamination can quickly lead to regulatory authorities potentially imposing costly penalties, with the consequent damage to suppliers' reputations.

Finally, another critical aspect of ensuring regulatory compliance is the establishment of standard operating procedures (SOP). Developing and implementing standardised procedures for all cold-chain activities helps business partners adjust transportation and warehousing operations as needed. These procedures should include protocols for temperature monitoring, handling practices, corrective actions in the event of deviations, and equipment maintenance. Reliability in cold-chain operations is further supported by the documentation generated and secured throughout the supply chain (Li, 2023), ensuring con-

sistency and ongoing compliance with regulatory requirements. By adopting robust cold-chain practices and focusing on regulatory compliance, companies can preserve the integrity and safety of temperature-sensitive products across the supply chain. This not only protects public health but also builds market trust and facilitates global trade, supporting overall supply chain operations. Additionally, when coupled with marketing efforts that emphasise sustainability goals, such practices can effectively meet customer expectations and enhance brand reputation.

Cold-chain infrastructure provides the flexibility necessary for businesses to respond to fluctuating environmental conditions, enabling them to adapt and thrive in dynamic and increasingly unpredictable environments. Climate change is exacerbating the frequency and severity of extreme weather events such as droughts, floods, and heatwaves, making it increasingly difficult to sustain supply chain operations under adverse weather conditions. As a result, cold-chain infrastructure plays a crucial role in enhancing supply chain resilience, particularly for products sensitive to temperature fluctuations. This infrastructure allows businesses to maintain operational continuity and thrive even amidst changing environmental conditions. Extreme weather events can disrupt transportation routes, damage infrastructure, and interfere with power supplies, all of which can negatively impact cold-chain operations. Cold-chain infrastructure, which includes refrigerated storage facilities, insulated packaging, and controlled atmosphere transport systems, ensures that optimal temperatures are maintained despite external disruptions (Q. Chen, 2022), which is essential for ensuring product quality and safety during environmental disturbances. Decreasing additional risk potential is well documented and proven (X. Chen et al., 2022). Furthermore, rising global temperatures, particularly heatwaves, exacerbate logistics costs and the potential spoilage of goods in transit. A robust cold-chain infrastructure addresses this by means of alternative transportation methods, such as refrigerated trucks or air cargo, even when traditional routes are hindered by weather events or damage to infrastructure. Real-time monitoring systems provide valuable data, enabling businesses to adapt their supply chain operations accordingly. Moreover, advancements in sensor technology and data management systems facilitate real-time temperature monitoring throughout the cold chain, enabling companies to respond proactively to any temperature deviations caused by environmental factors (Osorio, 2017). This capacity for quick corrective action minimises the risk of product loss or spoilage. Investing in resilient and flexible cold-chain infrastructure is not only essential for maintaining product quality but also for enhancing agility in the face of environmental uncertainty. By ensuring the ability to adapt to disruptions, businesses can minimise supply chain interruptions and continue to thrive in a dynamic global

market. Timely and error-free delivery is particularly critical in lean operations, where safety stock is minimal or non-existent. As such, maintaining an efficient delivery schedule has operational and marketing significance, further emphasising the importance of resilient cold-chain systems.

One of the key principles of Green Supply Chain (GSC) Management is its integration of waste reduction strategies into daily operations. While incorporating reverse logistics streams to promote the reuse or recycling of products and materials, minimising waste should always take precedence over efforts to recycle and reuse. The ultimate goal of an environmentally sustainable supply chain is to reduce unnecessary waste. Cold-chain technologies are instrumental in achieving this goal by extending the shelf life of perishable products, which in turn minimises waste within the supply chain and throughout the food production cycle, from farm to fork. Scientific evidence supports the role of cold-chain technologies in waste reduction. The Food and Agriculture Organization (FAO) estimates that one-third of global food production is lost or wasted (Gustavsson et al., 2011), resulting in substantial environmental consequences, including wasted water, land, and greenhouse gas emissions. Perishable goods such as fruits, vegetables, and meat are particularly vulnerable to spoilage due to microbial growth and biochemical degradation. By extending this shelf life and minimising waste, cold-chain technologies optimise resource usage across the entire food supply chain.

Furthermore, a reduced environmental footprint through lower water usage is another significant objective within green supply chain practices. Decreased food spoilage translates into less water wastage during production, transportation, and storage. In addition, reduced land use helps mitigate environmental impacts, benefiting producers, distributors, and consumers alike. Many businesses highlight their water savings in marketing campaigns to attract environmentally conscious customers. Food production is also land-intensive, and less food waste directly reduces the demand for agricultural land. Another critical area of focus within supply chain sustainability is the reduction of greenhouse gas emissions, particularly those associated with transportation operations. However, food waste also contributes to greenhouse gas emissions, including methane released during decomposition (Aramyan, 2021). Therefore, by minimising food waste, cold-chain technologies indirectly alleviate some of the environmental burden associated with global logistics operations, particularly emissions linked to transportation and food decomposition.

The energy source is a key aspect in assessing CCT technologies. The environmental impact of cold-chain technologies is therefore a multifaceted issue, encompassing both positive and negative aspects. Cold-chain technologies play a significant role in reducing the spoilage of perishable goods, thereby min-

imising food waste. Such waste reduction lessens the environmental burden associated with food production, such as water consumption, land use, and greenhouse gas emissions. Additionally, cold-chain technologies often reduce the need for chemical preservatives in food products, as optimal temperature control inhibits microbial growth, resulting in potentially healthier products while minimising the environmental impact associated with the production and disposal of chemicals. Advancements in cold-chain technologies have also led to improvements such as enhanced insulation materials, energy-efficient refrigeration systems, and route optimisation software. These innovations contribute to reducing energy consumption compared to older technologies (Meneghetti & Ceschia, 2020). However, the energy demand of refrigeration units used in storage facilities and transportation remains significant, potentially contributing to greenhouse gas emissions, depending on the energy source. Traditional refrigerants used in some cold-chain systems are potent greenhouse gases, and while strict regulations are phasing out certain harmful refrigerants, leaks and improper disposal of older refrigerants continue to pose a threat to the climate (Dong, 2021). Furthermore, disposable packaging materials used in cold-chain logistics generate waste.

Fortunately, recent developments in reusable and recyclable packaging materials provide more sustainable alternatives, along with other environmentally friendly advancements in cold-chain technologies. Replacing traditional refrigerants with ammonia, carbon dioxide, or hydrocarbons, which have lower global warming potential, offers a more sustainable option. Moreover, powering cold storage facilities with renewable energy sources, such as solar, wind, or hydroelectric power, significantly reduces reliance on fossil fuels and associated emissions. Additionally, utilising thermal energy storage systems enables the optimisation of energy consumption by storing excess cooling capacity during off-peak hours for use during periods of peak demand (Q. Chen, 2022). In regions where solar power availability is increasing, the opportunity to further reduce the carbon footprint is particularly promising.

Conclusions

While current cold-chain technologies still present particular environmental challenges, ongoing advancements are pushing the industry towards a more sustainable future (Bottani, 2019). Focusing on energy efficiency, the use of natural refrigerants, renewable energy integration, and waste reduction strategies will be essential for minimising the environmental impact of cold-chain operations and simultaneously strengthening risk mitigation plans (Kristanto et al., 2023).

As sustainability becomes an increasingly central component of supply chain management, particularly in the face of global warming, cold-chain technologies present a significant opportunity to support the long-term viability of global logistics operations while advancing environmental goals.

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