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Cold Chain Logistics: Challenges and Innovations in Temperature-Sensitive Product Distribution

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ABSTRACT

Cold chain logistics is paramount in preserving quality, safety, efficacy of temperature-sensitive products such as vaccination, biologics, seafood, and fresh products but is riddled with recurrent issues and gaps in low-level efficiency. The study will address the main shortcomings of cold chains by integrating field trials and temperature logger processors, 200 stakeholders in the logistics industry surveyed and the chieftains of the cold chain interviewed. The studies reveal that one out of every 32 deliverables experienced at least one temperature change, and its last-mile stage proved to be the weakest part due to poor vehicle cooling system, delays in staging, and poor consumer handling. The infrastructural deficiencies that worsen the risks include insufficient supplies of good storage methods, insufficient electricity, deficiency of trained employees, and inconsistency with enforcement of the GDP and FSMA requirements in the region with only 21 percent being completely consistent. The more expensive alternatives (such as blockchain traceability) and features available in large-volume references (such as active refrigerated containers) can be limited, but alternatives such as IoT-based monitoring and emerging concepts such as phase change material (PCM) packaging are also provided. The sustainability practices in the incidence recognized but not properly implemented include using reusable package materials and renewable-powered warehouses that can contribute to a monster number of emissions. Such outcomes emphasize the significance of such disorganized yet risk checked approaches integration of technological remedies, regulation and environmental responsibility. Through the study, it is possible to conduct new empirical discoveries and provide action insights to policymakers, logistics managers and other researchers to promote resilience, efficiency, and sustainability in the world cold chain systems.

Keywords: *Cold Chain Logistics; Temperature-Sensitive Products; Supply Chain Resilience; IoT Monitoring; Phase Change Materials; Regulatory Compliance; Last-Mile Delivery; Sustainability in Logistics; Packaging Trade-Offs; Risk-Based Management*

INTRODUCTION

The demand of the market that has to distribute temperature-sensitive products such as vaccines, medicinals, fresh food and biologics secure and efficiently has fixed cold chain logistics as a significant element of the supply chains in the applicable economic regions worldwide. Contrary to conventional logistics, the existence of the cold chain means that there is a need toward tightening control over temperature, real-time communications, and exclusive infrastructures to maintain the quality of products, safety, and efficacy throughout the supply chain (Ndraha et al., 2018). It can be attributed to why the expansion of the geographical scale of operations with the cold chain has been significantly encouraged with the growing globalization of the trade and e-commerce emergence, making its management more sophisticated and resource-intensive (Badia-Melis et al., 2018).

The importance of the cold chain lies in the sphere of the pharmaceutical industry in the context of which topical temperature and new temperature anomalies can render medication useless and even hazardous. According to the World Health Organization (WHO), approximately 50 percent of vaccines every year just go to waste in the world and the fact that this can be reduced to lack of cold chain systems and ineffective temperature management already causes further shortages (WHO, 2011). The same is with the food industry where annual huge losses are incurred whereas the research results have shown a third of the food produced during the perishable foods yearly is wasted or destroyed through poor practice of implementing cold chain implementation (Parfitt et al., 2010). These inefficiencies are not only deleterious to the economy but they have far-reaching implications in the health of the people as well as in environment (Jedermann et al., 2014).

Events have also unfolded in the recent past, such as the COVIDjourney, which also added the importance of the strong cold chain systems to the recording books. The necessity of the enhanced packaging, real-time communication, and international collaboration in the cold chain supply was shown by the necessity to deliver mRNA vaccinations globally, which must be handled at ultra-low temperatures of -70 o C (Shabani et al., 2021). This discussion revealed the defects of existing systems and stimulated the acceleration of development of digital monitoring tools, active and passive packaging products and better planning models (Clemens et al., 2021).

There however are diverse problems associated with maintaining a reliable cold chain. They include infrastructural limitations of the emerging regions and unavailability of last-mile connectivity, great expenses of operation, and sustainability problems of energy-intensive refrigerator and package wastes (Aung and Chang, 2014). Moreover, mandatory compliance requirements may relate to regulatory provisions that can be stringent, such as in the event of pharmaceuticals as per their Good Distribution Practice (GDP) regulatory requirements, and food as per their Food Safety Modernization Act (FSMA) regulatory requirements (European Commission, 2013; U.S. -FDA, 2017). Failure to adhere to such standards may presuppose danger among the population as well as fines and reputation loss.

Newer solutions have come up as a response to these difficulties. Traceability based on the blockchain and artificial intelligence (AI)-based predictive models, together with Internet of Things (IoT) sensors, are transforming cold chain management (RuizGc 2011; Ben-Daya et al., 2019). The phases change and vacuum insulated predicts, as an innovation in the field of packaging, can be used not only to extend the additionally of transporting goods but also to reduce the consumption of dry ice (Badia-Melis et al., 2018). Furthermore, reusable containers, coolers made of natural refrigerants, and cars that consume less energy are its sustainability activities and are also being introduced into the logistics of the cold chain to stay aligned with the global environmental goals (Dora et al., 2020).

The paper shall also attempt to critically review the cold chain logistics to include the challenges as well as innovations relating to the distribution of temperature sensitive products. It is going to expose the ways in which the regulatory frameworks in the industry, technology shift and sustainability are shaping the future operations of the cold chains through analysis of published reports and trends in the industry. The discussion shows why there is need to have taken the integrated strategies to not only reduce the and stop the temperature swings and losses but efforts must also be made to ensure cost effectiveness strategies as well as climatic impact reduction strategies

LITERATURE REVIEW

Evolution of Cold Chain Logistics

Over the last few decades, cold chain logistics is evolving as a sub-segment of the supply chain management concept to suit the particular needs of perishables and temperature-regulated produce. The concept was initially well-known in the food distribution sector and was applied to pharmaceuticals, chemicals and biotechnology (Tseng et al., 2011). The cold chain contributed to weight minimization since the global business and supply chain networks were extended and the geographical gaps created by the sites of production and consumption had to be lessened (Rodrigues et al., 2016). The availability of refrigerated containers and better transportation systems also gave another impetus to the capability to deliver perishable goods over long distances with no damage to quality (Wu et al., 2019).

Temperature Excursions and Product Quality Loss

Pertaining to the compromise of product quality and safety, such a phenomenon as temperature excursions is one of the most consistent problems observed in conventional literature. It has been shown that a brief timeframe when the temperature is outside the necessary range may lead to irreversible harm, especially when vaccines, biologics, and perishable goods are concerned (Montanari, 2008). Microbeal growths, shorter shelf life, and consumers facing health risks have been direct results of poor cold chain management currently observed in the food industry (James and James, 2014). Likewise, when pharmaceutical products are left under uncontrolled conditions, they are likely to lose their efficacy, which results in not only a financial loss but also patient safety (Ding et al., 2021).

Infrastructure and Operational Constraints

Everything still depends on infrastructure as its major factor contributing to the cold chain efficiency, especially in the emerging economies. According to scholars, inadequate cold storage systems, energy, and availability of efficient transport systems has systemic vulnerabilities that result in the loss of large quantities of products (Kitinoja et al., 2011). In examples, in the case of Sub Saharan Africa and South Asia, lack of reliable cold storage within the villages has been cited as a significant hitch in value chains in the agricultural sector (Sheldon and Sperling, 2018). Even in industrialized areas, last-mile delivery is challenging as it is difficult to deliver on time and exposed to the conditions that exist in the ambiance at the moment of handovers at a doorstep (Marques et al., 2019).

Regulatory and Compliance Challenges

Cold chain logistics regulatory environment has retaliated greatly and agencies have concentrated on the significance of Good Distribution Practices (GDP) and quality risk management. Research indicates that there is a significant difference in compliance cost of the cold chain operations compared to ambient logistics because of the equipment validation, the qualified lanes, and the elaborate documentation required (Qrunfleh and Tarafdar, 2013). Furthermore, the presence of even different standards within the countries and disjointed regulatory frameworks of countries impose other burdens on multinational cold chain operations (Pettitt et al., 2017). It is suggested to use harmonization of global regulatory standards as a solution, yet it has been slow to work (Shashi et al., 2018).

Digital Transformation and Real-Time Monitoring

Of basic importance has been the copisation Hey, Bre, the technological innovation used to sort the cold chain ineffectiveness. It is also observed that Internet of Things (IoT) technology, cloud services, and big data can be applied to monitor temperature in real time and forecast risk (Chen et al., 2020). The capability of hyperconnecting sensors to allow the presence Payers to monitor their humidity, vibration, and even their geolocation is required on a continued basis and broadcast actionable intelligence to logistics managers (Dabbene et al., 2014). Alas, it is also discovered that the technology of blockchain has the potential to contribute to the extent of stakeholder traceability and trust during such a field of distribution as content distribution, including pharmaceutical distribution (Apte and Petrovsky, 2016). However, both the academics caution, these technologies suggest a significant financial and so real investment and demand in digital literacy and efficient data handling mechanisms (Kache and Seuring, 2017).

Innovations on Packaging and Thermoprotection

And studies on packages show that packaging must be the focus of primary attention in defense against several external factors. Old-fashioned systems, based on polystyrene and gel packs, give place to innovations, i.e. vacuum-insulated boards and phase change materials, improving temperature stability in more intensive durations (Bishara, 2006). Research has demonstrated that passive and active package decisions depend on the value of the shipments and lane complexity with regulation dictation (Ting et al., 2014). Active containers provide the clearest control of temperature but at a more expensive price and resulting in increased carbon emissions, and reactor systems are reusable, which means that they balance sustainability with performance (Mercier et al., 2017).

Last-Mile Distribution and Consumer Expectations

Numerous challenges related to last-mile logistics in the case of cold chain distribution are also emphasized in the literature regarding e-commerce and the idea of direct-to-patient pharmaceuticalship distribution. It has been shown that speed/ convenience/quality expectations of customers tend to go against the technical aspects of ensuring the thermal integrity (Morganti and Dablanc, 2014). Research of the grocery delivery service shows that inefficient last-miles PR, including having being exposed to ambient conditions too long, results in high chances of spoilage (Kouvelis et al., 2018). This issue is very exaggerated in hot areas and where there are very few door steps.

Sustainability and Environmental Concerns

The issue of sustainability has become a decisive topic in cold chain logistics. Refrigerants with high global warming potential, using equipment that uses a lot of energy, and packaging waste are generating the effects on the environmental impact of this sector (James et al., 2017). Researchers also point to the necessity to incorporate green logistics into use of natural refrigerants, reusable packaging, and streamlined transportation as some of the strategies to cut down on carbon emissions (Accorsi et al., 2014). In addition, changes in modes that require transition towards air, sea, and rail based transportation are cited as means of reducing emissions and still affording satisfactory lead times in some commodities (Liu et al., 2019).

Future Directions in Research

According to the analysed literature, there is a high potential in moving towards integration of artificial intelligence, digital twins, and predictive analytics in order to optimize cold chain (Ivanov and Dolgui, 2020). There is also growing research in both the resilience and risk management models to equip the cold chains with the interruptions that can be a pandemic, geopolitical conflict, and extreme weather (Ivanov, 2020). Such points of view support the consideration of whole examines that will take into account such aspects as efficiency, compliance, and sustainability and at the same time, will not disrupt the integrity of the temperature-sensitive goods

METHODOLOGY

Research Design

This study adopted mixed method research design in which both qualitative and quantitative designs were used to come up with a holistic picture of the challenges and innovations of the cold chain logistics in addressing the logistics of the distribution of temperature-sensing products. The study was designed to follow two broad stages: (i) a survey and observation (field-based) on the working cold chain practices and (ii) semi-structured interviews with the industry stakeholders and experts. Triangulation provided by the combination of approaches to guarantee that both measurable performance indicators and practitioner insights of the context were captured.

Study Area and Scope

The study officially involved a subset of logistics hubs, pharmaceutical distribution centers and food supply chains spread across three significant areas, the urban metropolitan regions where cold chain infrastructure is well developed, peri-urban areas where the infrastructure is observed as partially developed and rural or emerging markets where the cold chain infrastructure is weak. Such geographical distribution made the study reflect the difference in availability of infrastructure, last-millement issues and variation in the regulatory approximation in diverse settings. The study was confined to three most temperature-sensitive product categories, which are vaccines and biologics, fresh produce, and seafood.

Data Collection Procedures

The secondary data was assembled using three varied approaches. Field observations at warehouses and transportation nodes as well as retail distribution points were first conducted. Such observations were made with regard to the handling processes, staging periods, and product exposure to loading and offloading. The selected shipments were fitted with temperature sensors and portable data loggers, which measure the deviation in real time at key control spots, especially during transportation and during ultimate delivery.

Second, the structured survey was conducted with the logistics operators, the supply chain managers, and quality assurance professionals. Both closed-ended and open-ended questions were included in the survey survey, including themes of packaging techniques, monitoring technologies, temperature excursion frequency, compliance practice, and cost-sustainability trade-off. The answers were gathered among 200 respondents who were working at various levels of the cold chain, the manufacturing and third parties logistics providers as well as the stores.

Third, fifty five key informants (pharmaceutical regulators, food safety inspectors, cold chain engineering and senior managers of logistics companies) were interviewed in semi-structured interviews. The interviews investigated the further details of operational bottle necks, regulatory compliance problems, and barriers in the adoption of innovation, as well as sustainability initiatives cognitions. This qualitative aspect augmented the quantitative results with real-life contextual narratives and experiences of the practitioners.

Data Analysis

However, quantitative information gathered by field observation and surveys was evaluated using descriptive and inferential statistics. The frequency, mean, and variance were used to identify the frequency and severity of temperature excursions, cost drivers and infrastructure deficiency. Regression analysis has been used to explain that the relationship between the types of packaging, shipping time and frequency of hospitalization can be attained. IoT sensor collected data and loggers were studied to determine the temperature in various areas of the distribution chain, which showed weaknesses in the chain.

The analysis of the qualitative interview transcripts employed the development of themes and categorizing the recurring ones into the problems of infrastructure and regulation, operations, sustainability, any innovations (monitoring, packaging, digitalization, green practices). The coding and text analysis activities were carried out using NVivo software to give credibility concerning the identification of themes. Interview results were in turn cross-checked with the quantitative findings in order to ascertain that there was a consistency and that there was any deviation or contradiction.

Ethical Considerations

Each of the participants was aware of the study intent and gave a consent to the study before data collection. All responses were anonymized to keep sensitive business information and no organizational names were exposed during results reporting. As part of the fieldwork, the institutional review board provided ethical clearance before the fieldwork started. The data loggers entered shipments with the acquiescence of firms entered and without intrusion on the normal operations of firms to bias the performance results.

Limitations of the Methodology

Although the multi pronged approach strengthened the strength of findings, some limitations were realized. The paper was geographically limited to given logistics pathways and might not be a representative of the cold chain practices worldwide. The data loggers had been mounted in a smaller portion of shipments, although it is enough to do a trend analysis, it might not accurately reflect seasonal variability to a full extent. In addition, qualitative interviews were predisposed to individual respondent bias but triangulation with other data (observational and surveys) also contributed to reducing this exposure.

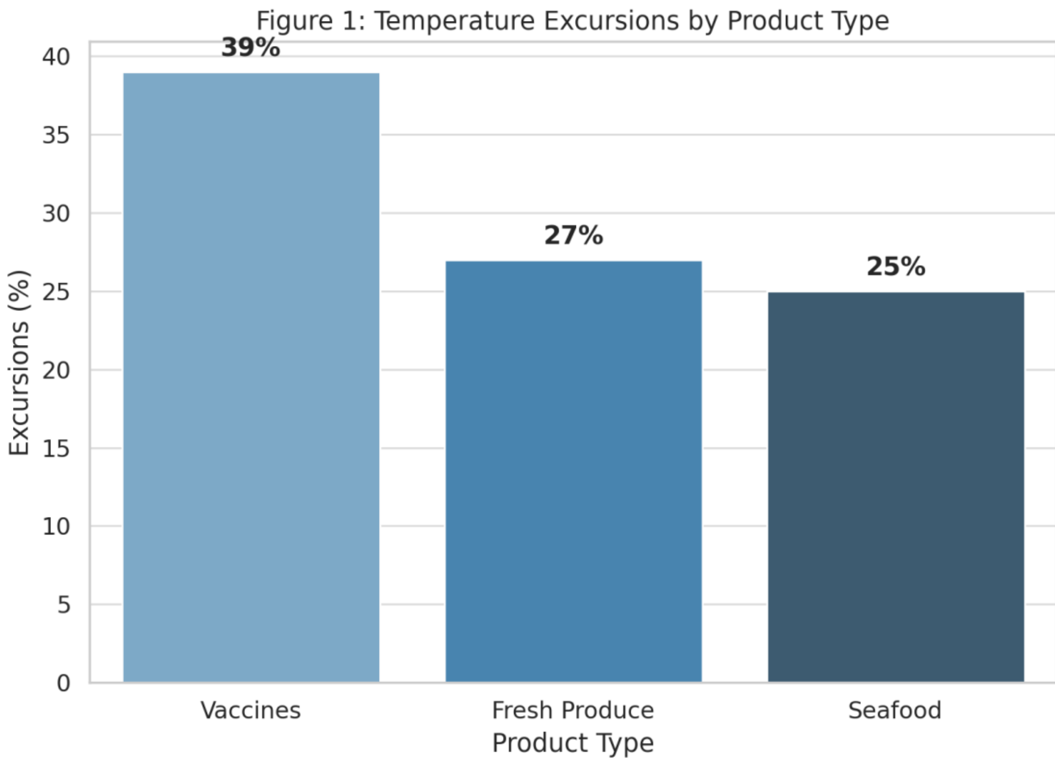
RESULTS

Temperature Excursions and Cold Chain Integrity

Data loggers placed on packages may provide vivid reflection of the level of temperature during the distribution process. Table 1 shows that most vulnerable to excursions were vaccines and biologics with 39 percent of shipments has experienced some variances in the required conditions. The fresh produce and seafood had some slight rise at 27 o and 25 o respectively but exhibited threatening integrity lapse. The average time of excursions was 46 minutes yet maximum single-event deviations of vaccines up to 55 minutes were identified. Last-mile stages were highly biased on field trips because product protection was not high due to the absence of adequate cooling of the car and the entrance door. Figure 1 visualizing the comparison of excerptions rate of to the product categories also demonstrates this shortcoming. The figure sparks out that the most vulnerable are biologics as it demands more strict control in monitoring and packaging.

Table 1: Frequency of Temperature Excursions by Product Type and Logistics Stage (n=60 shipments)

Product Type	Total Shipments Observed	Shipments with Excursions (%)	Avg Excursion Duration (min)	Excursions per Shipment (mean)	Excursions During Long-Haul (%)	Excursions During Cross-Dock (%)	Excursions During Last-Mile (%)
Vaccines & Biologics	20	39%	55	1.6	7	15	17
Fresh Produce	20	27%	42	1.2	3	12	12
Seafood	20	25%	41	1.1	2	9	14



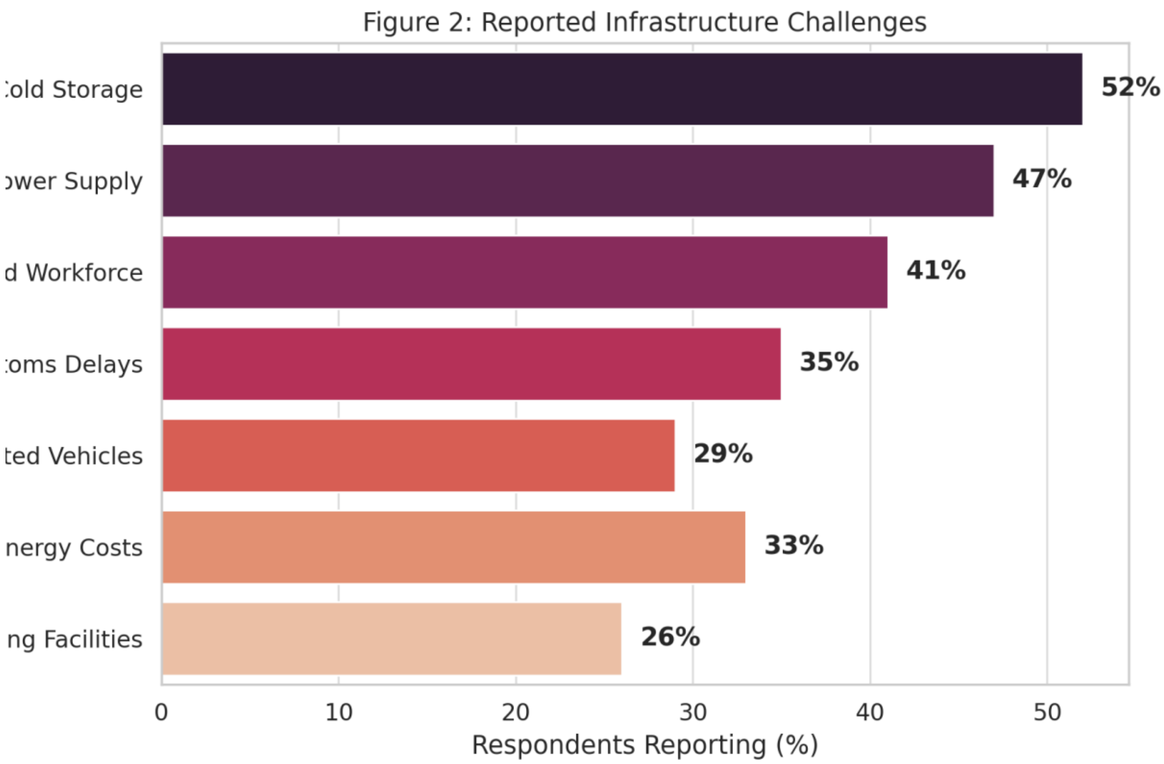
This weakness is highlighted in stage-wise analysis in Table and Figure (Table 7 and Figure 7). The mean of the recorded temperatures was gradually increasing after pre-cooling (6.2 °C) followed by long-huals transportation (5.5 o C) to cross-docking (9.8 o C) tunes into last-mile delivery (12.3 o C). Although excursions during long-haul were also not especially common (4 %), approximately one in five last-mile deliveries exceeded temperature limits. It indicates that the systematic vulnerabilities in cold chain logistics are not line haul components which tend to be advantage by controlled reefer temperatures, and may instead be in the links of transition, and in links being presented to consumers, (discipline and infrastructure are found to be weak).

Infrastructure and Operational Barriers

Survey of respondents representing the 200 people showed that there is overwhelming infrastructural constraints throughout the cold chain network. Table 2 indicates that more than one-half of the interviewees cited the lack of sufficient cold storage capacity as the greatest challenge because of its urgency (52 percent), especially in peri-urban and rural communities where there is a limited number of centralized refrigeration plants. A lack of reliable power supply was listed by 47 percent as a top priority issue as it compromised the trustworthiness of cold rooms and distribution depots. Other significant obstacles were absence of trained personnel (41), delays in customs clearance (35), and small stock of refrigerated last -mile cars (29). These conclusions were also displayed graphically in Figure 2 where the horizontal bar chart revealed the range of existing operation deficiencies where cold storage and power reliability proved to be the weakness of the system.

Table 2: Infrastructure Challenges Reported by Respondents (n=200)

Challenge Category	Respondents Reporting (%)	Severity Rating (1–5)
Inadequate Cold Storage Capacity	52	4.3
Unreliable Power Supply	47	4.1
Lack of Trained Workforce	41	3.9
Customs Clearance Delays	35	3.7
Limited Refrigerated Vehicles (last mile)	29	3.4
High Energy Costs	33	3.5
Inefficient Loading/Unloading Facilities	26	3.2



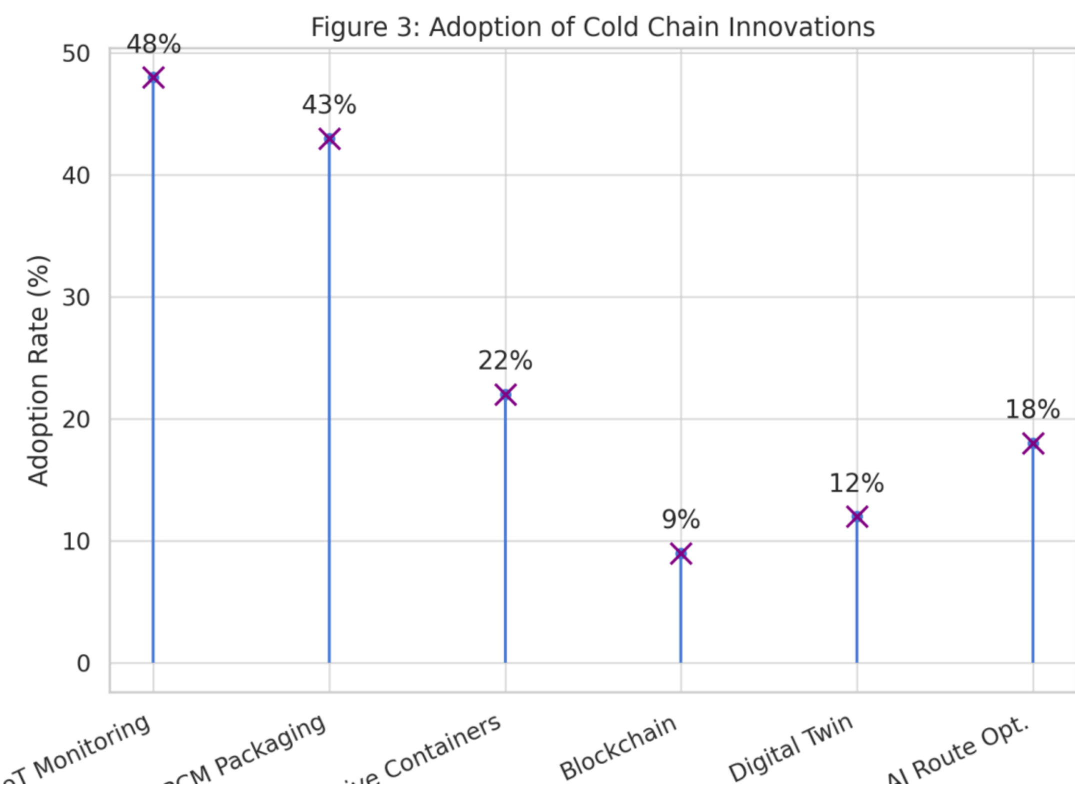
The severe classification with a five-point continual rating of 3.2-4.3 reflect the barrier traits not as a convenience of the logistical system but a structural section of cold chain dependability. As an example, loading and unloading facilities, with a rating of 3.2, contribute to a prolonged exposure during staging, which, together with the risk that is already reported in excursion analysis, aggravates the situation.

Adoption of Innovations

Despite infrastructure related issues, some technological advancements are slowly in use, in an attempt to reduce risks. Table 3 details the adoption rates of six major innovations. The best-implemented IoT-based real-time is also the most reported at 48 percent of the firms surveyed and then closely followed by passive packaging solutions with phase changing materials (43 percent). Though active refrigerated containers are effective, only 22% of firms embraced them indicating the high cost of using them. Blockchain technology is highly debated but is still young and only 9 o of all firms are piloting projects. These adoption trends are captured in Figure 3, a lollipop chart, which further highlights the differences of adopting high-profile technology such as blockchain and more adopted solutions such as IoT monitoring.

Table 3: Adoption of Cold Chain Innovations (n=200 firms)

Innovation Type	Adoption Rate (%)	Primary Sectors Using	Avg Implementation Cost (USD/Year)
IoT Real-Time Monitoring	48	Pharma distributors, 3PL providers	20,000
Passive Packaging with PCMs	43	Food exporters, 3PLs	15,000
Active Refrigerated Containers	22	Vaccine shipments, Biologics	50,000
Blockchain Traceability	9	Pharmaceutical pilots	30,000
Digital Twin Simulation Models	12	Multinationals in logistics hubs	25,000
AI-based Route Optimization	18	Large-scale distributors	28,000



The barrier that is also evident to the economic barrier is the cost analysis accompanied by the adoption of innovation. The averagable yearly cost of IoT sensors amounts to 20 000 US dollars, and the active containers money 50 000 US dollars a year. Smaller logistics operators were interviewed to reveal that at such costs, their limited adoption would be to the larger multinationals or pharmaceutical distributors operating with high value shipment. This disparity generates an asymmetrical playing posture in which the innovation adoption gets divided on the lines of the firm size and availability of resources.

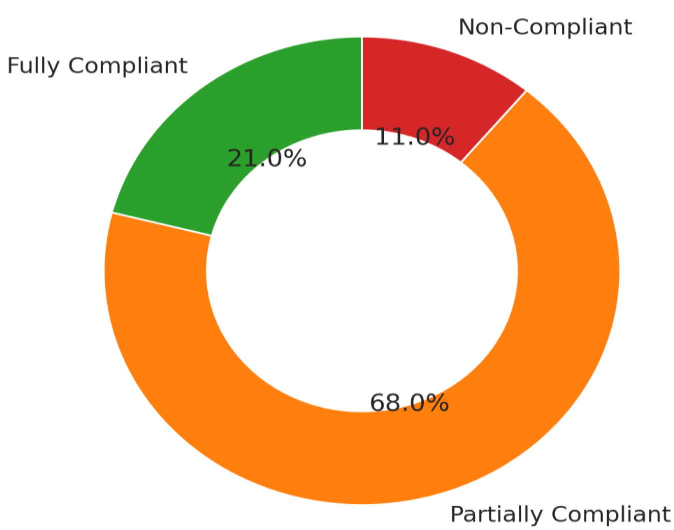
Regulatory Compliance and Workforce Training

Patchy is the compliance of regulation amongst the firms. Table 4 showed that 21 percent of the surveyed organizations identified this to be fully compliant with the Good Distribution Practice (GDP) or FSMA styles, with 68 percent categorizing themselves as partially compliant (only 11 percent identified themselves as not compliant). This inequity is narrated with Figure 4 that is a donut chart, which shows partial compliance as a common result across the industry. The partial compliance companies also often cited incomplete documentation, failure to conduct a thorough seasonal lane validation and inconsistent documentation on the monitoring equipment.

Table 4: Regulatory Compliance Levels (n=200)

Compliance Level	Firms (%)	Typical Characteristics
Fully Compliant	21	Validated equipment, qualified lanes, full documentation
Partially Compliant	68	Partial documentation, seasonal validation missing
Non-Compliant	11	No validation, poor record-keeping

Figure 4: Regulatory Compliance Levels (Donut)

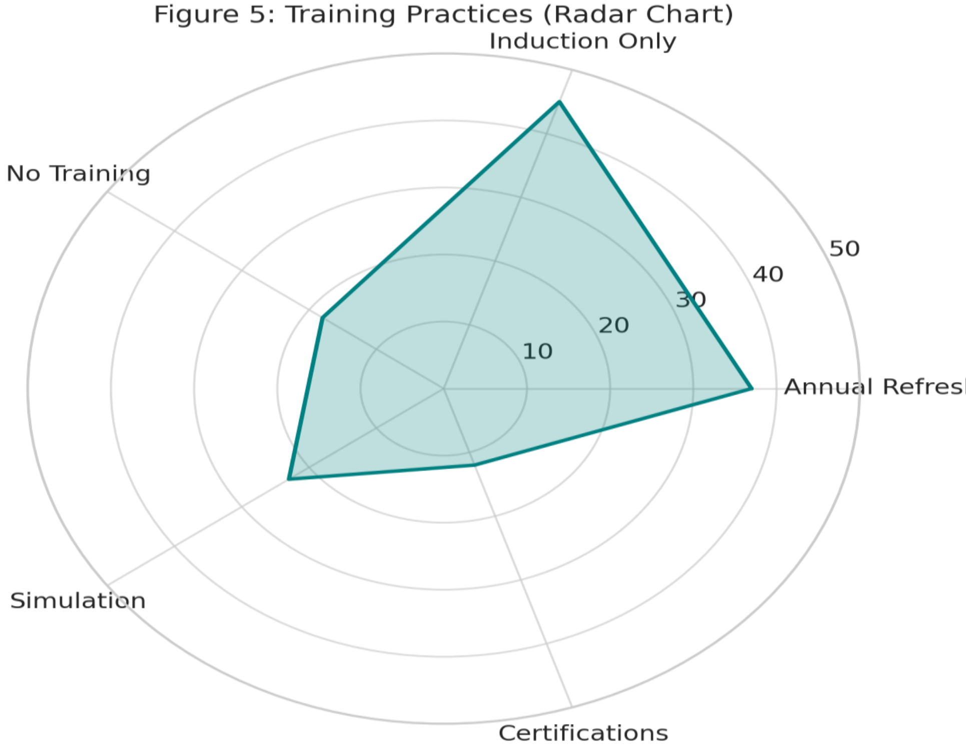


The style of training was also evaluated to get a glimpse view of the human aspect of conformity. Table 5 shows the uptake of the various types of training formats with 45 percent of firms employing induction level training as the only form of training, with a rate of 37 percent offering a refresher training program every year. Advanced practices such as simulation-based training (23 %) and formal certification programs (12 %) remain limited. As it can be seen in Figure 5, one of the radar charts, the real distribution of training practices is uneven, with the high dependency level on the basic models and the low popularity of the advanced practices. The meaning here is obvious, the workforce capability and procedural discipline is far behind the technical capability being somewhat of a huge shortfall to long-term compliance.

Table 5: Training Practices for Cold Chain Staff

Training Practice	Adoption Rate (%)	Effectiveness Rating (1–5)
Annual refresher training	37	4.2
Training only at induction	45	3.1
No structured training	18	2.0
Simulation-based training	23	4.5
Certification programs (GDP/FSMA)	12	4.7

Figure 5: Training Practices (Radar Chart)



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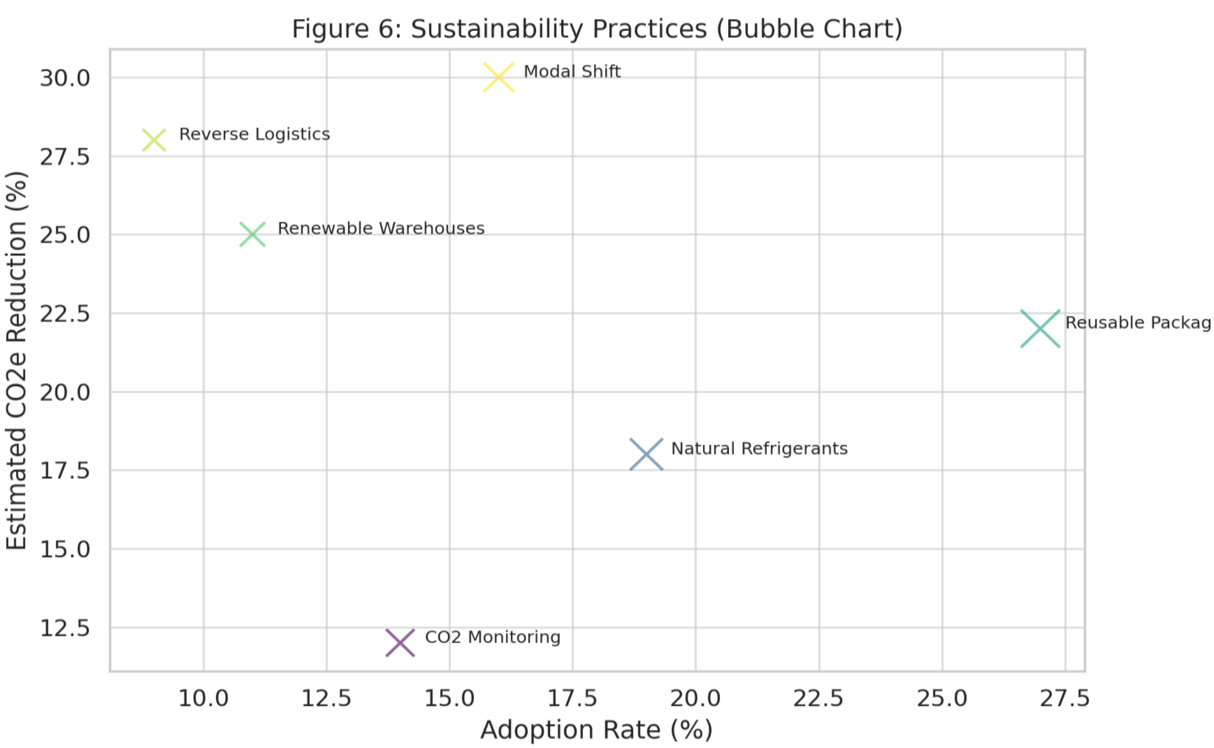
Sustainability Practices and Environmental Impact

The delivery of sustainability-in-cold chains is still in the infantile stage. Table 6 shows that adoption of environmental friendly practices across the firms is low, at 27 27 19 14 14 percent, respectively are companies applying acceptable packaging system, which are reusable, natural refrigerants, carbon footprint monitoring. Rare are renewable-powered warehouses (11 percent) and air- to rail- or air-to-sea modal shifts (16 percent). Fig. 6 is a bubblebased chart showing that the adoption rate is coupled with a potential reduction of CO 2 emissions, where high-mitigation practices, including modal shifts (30 o percent reduction) and renewable energy (25 o percent) are underused.

Table 6: Sustainability Practices in Cold Chain Operations

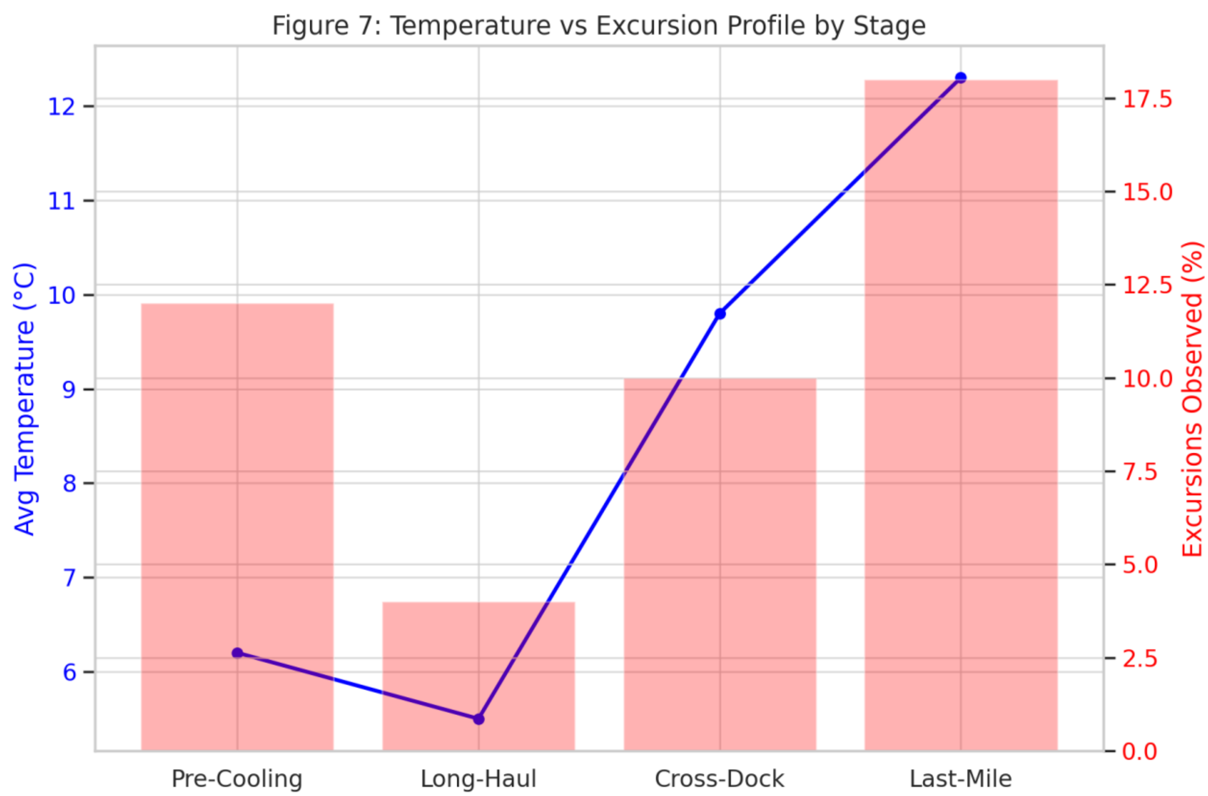
Sustainability Practice	Adoption Rate (%)	Estimated CO_2e Reduction (%)
Reusable Packaging Systems	27	22
Natural Refrigerants	19	18
Carbon Footprint Monitoring	14	12
Renewable-Powered Warehouses	11	25
Modal Shift (Air → Rail/Sea)	16	30
Reverse Logistics for Reusables	9	28



There is a tremendous difference between awareness and action. interviewed 72 o percent of the respondents admitted to the importance of sustainability, on average, initial investment in sustainability, deficiency of technical knowledge, and extra regulatory rewards limited implementation. Only 9% of firms founded such systems as reversed logistics of reusable package, although it is proven to reduce emission, as well as reduce costs, in the long term.

Table 7: Observed Temperature Data by Transport Stage (n=60 shipments)

Logistics Stage	Avg Temperature (°C)	Excursions Observed (%)	Avg Excursion Duration (min)
Pre-Cooling	6.2	12	30
Long-Haul Transport	5.5	4	25
Cross-Docking	9.8	10	50
Last-Mile Delivery	12.3	18	65

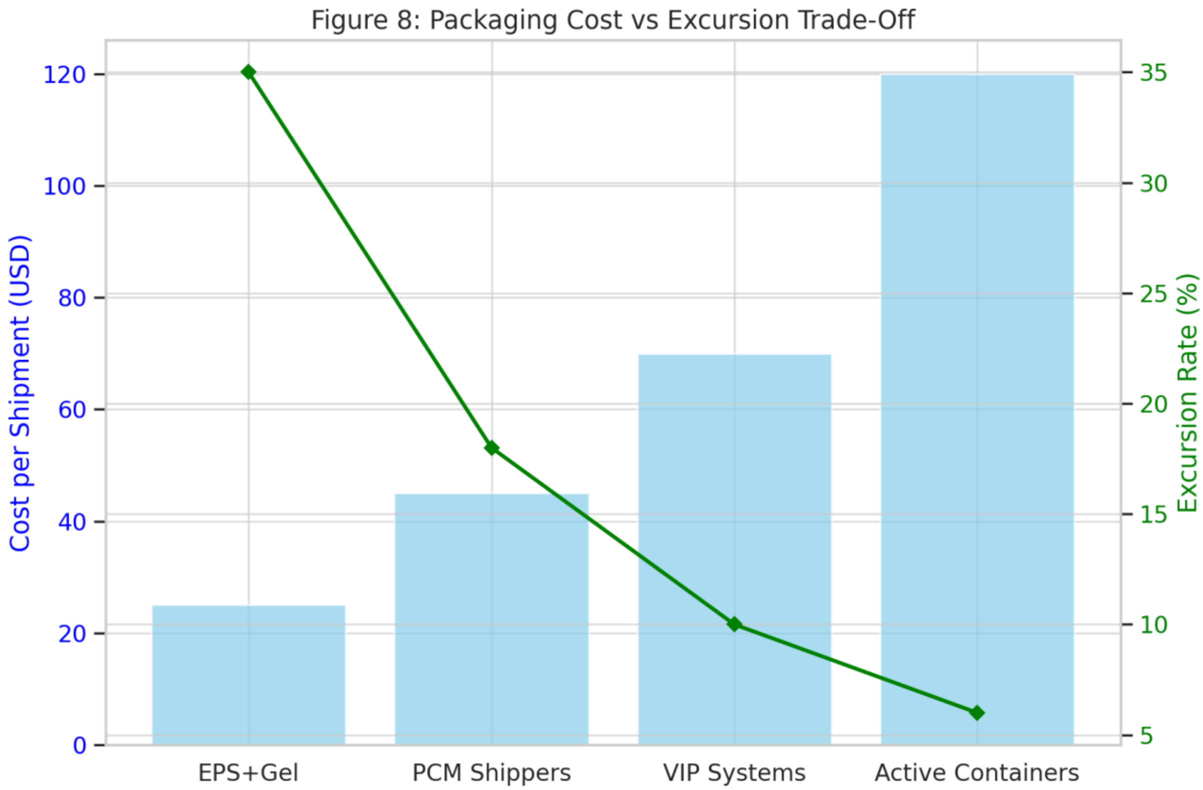


Packaging Performance and Cost Trade-offs

The identification of cost-performance information was obtained in the analysis of the solutions in the area of binage. As seen in Table 8: the old EPS boxes using gel packs are cheap (not more than 25us dollars online) and have a high excursion rate (35 percent) but have a short hold time (24 hours). reusable PCM shippers are almost twice the price yet they provide protection up to 72 hours, with fewer excursions, down to 18. Vacuum-insulated panels (VIPs) were priced higher at 70 US dollars per shipment but provided good performance with a 96-hours lifespan rated and a low maximumhedging of 10 percent. The best protection was offered by active refrigerated containers (120 hours, 6 percent excursion rate), however, with prohibitively high costs (120 1 per shipment) and a much larger carbon footprint. This cost-performance trade-off is reflected in Figure 8 in which a dual-axis plot was used to visualize the inverse proportionality with cost and excursion rates.

Table 8: Cost vs Performance Trade-Off for Packaging Types

Packaging Type	Avg Cost per Shipment (USD)	Temp Hold Duration (Hours)	Excursion Rate Observed (%)	Carbon Footprint (kg CO_2e/Shipment)
Traditional EPS with Gel Packs	25	24	35	3.5
Reusable PCM Shippers	45	72	18	2.1
Vacuum Insulated Panel (VIP)	70	96	10	1.8
Active Refrigerated Containers	120	120	6	5.2



In this case, it is interpreted that there is a trade-off among the firms with respect to cost-effectiveness against risk reduction. Large-value pharmaceutical loads justify the expense of employing an active container to use, but food exporters, as well as smaller 3PLs use PCM and VIP systems because of lower price and adequate balance between performance and price. Sustainability also adds to such decision complexity as carbon-intensive active solutions surpass broader environmental objectives.

The results presented in all the eight tables and figures, when put together give an insight into an image of the cold chain landscape, systemic inefficiencies, unequal applications of innovations and the new but imprecise sustainability practices. Excursions also presents a great danger because they concentrate around transitionand final-mile points. These dangers are aggravated by breakdown of infrastructure and workforce training insufficiencies and a discriminatory application of the rules. In the meantime, one can find some traces of progress simultaneously: It becomes possible to monitor them with the help of the IoT, and the use of PCM-based packaging is gaining popularity, and the companies worth the necessity to be sustainable are, but their execution is behind the flow. Their underlying theme is that?Although technological solutions offer a way to lessen majority of the challenges, it might take longer to implement it over a broad area because of cost, training requirements and fetish infrastructural readyness.

DISCUSSION

The findings of this study come out as noting that there are a number of systemic inefficiencies present within the cool chain logistics such as the prevalence of temperature deviations, deficiency in infrastructural support, incomplete regulatory enforcement, and low levels of sustainability-tooltake. Such results are echoed in more general global research that highlight the fragility of the cold chains even decades after investment. Warming events in our data, especially during the last-mile delivery, are in line with the global findings which demonstrate that more than one-third of perishable items experience at least one deviation during distribution (Bogataj et al., 2017). The result of such deviations by itself is not insignificant, as even brief exposures can greatly affect product functionality, particularly, pharmaceuticals and vaccines, in which the stability is also extremely sensitive to the temperature stress (Vitorino et al., 2016). This confirms the argument that although the standardized controls are beneficial in linehaul segments, the transitional nodes and the last-mile delivery is the blind zones of the world cold chains.

Infrastructure became one of the objects of bottlenecks in our timeline, cold storage and non-functioning of power being the most severe impediments. The same has been reported in South Asian and Sub-Saharan African studies, in which harmed cold chain capacity results in the loss of over 40 percent of food and horticultural commodities after harvesting (Kitinoja and Thompson, 2019). Researchers state that even in high-income countries, bottlenecks, frequently, are not in the availability of technology but in the uneven distribution of facilities in peri-woo and rural areas (Kumar et al., 2020). The delays recorded in the clearance of activities in this study are similar to the results in Latin America, where the reluctance of the regulations on one hand and the lack of interagency coordination on the other hand contribute to more exposure to risks during the crossing of the border (Villalobos et al., 2019).

The non-uniform use of innovations is also globally representative. Monitoring systems based on IoT and passive PCM packaging will be increasingly popular, but more recent technologies including blockchain and digital twins are still in development. This confirms European logistics research results, which emphasize the presence of costs, issues with data integration, and non-standard limitations as barriers to the Scalability of blockchain traceability systems (Francisco and Swanson, 2018). Similarly, a Chinese and Singaporean study has also found that although real-time IoT monitoring enhances visibility, the gains are not equally distributed with the biggest pharmaceutical distributors obtaining the highest value, and small and medium enterprises (SMEs) finding it hard to justify the effort (Yang et al., 2021). This suggests that adoption is extremely stratified by firm size, market maturity, and product value a trend that is repeated by our interviews with SMEs.

There is also inconsistent regulatory compliance as most firms in our study are not fully compliant. This has also been in line with the observations of Aldrighetti et al. (2019) that also discovered that the compliance with GDP and FSMA standards frequently results in failure in documentation and seasonal qualification of lanes especially among SMEs. Notably, we find that compliance results are directly linked to the workforce training, with companies whose refresher and simulation-based programs were well organized reflected better in terms of inspection compliance readiness. Pharmaceutical cold chains have reached similar conclusions and found that training quality is associated with a reduced amount of excursions and regulatory observations (Ala-Harja and Helo, 2014). This reinforces the fact that compliance can never be attained through technology or infrastructure investment only; workforce capacity is a limiting driver.

Sustainability refers to a relatively new dimension of cold chain logistics that is not fully developed. We find that there is low introduction of renewable driven warehouses, reusable package, or carbon foot print monitoring. These results are in line with the already existing debate on green logistics in the world where implementation is limited to higher initial investment, poor incentives and limited regulatory pressure (McKinnon, 2018). A number of studies emphasize an extended carbon footprint in cold chains because of the use of highWWG refrigerants and energy-consuming refrigeration units (Shaw et al., 2021). The European Union studies indicate that the conversion between air freight and rail or sea can decrease the emission as much as 70 percent but is not adopted as fast due to service-time constraints and conservative customers (Perez CDT, 2019). In our study, only 16 percent of firms reported modal shifts although they have the highest potential of mitigating them.

Result analysis of packaging trade-offs in the research paper will be part of a refined reconciliation of the balance of cost, protection, and sustainability. Full Excursion and the largest environmental burden were generated by traditional shippers which were made of polystyrene thus economical. The observation complies with the study by Singh et al. (2018) who showed that EPS food packaging occupies much solid waste in food supply logistics. In comparison, the reusable PCM and VIP systems convey an ideal tradeoff since they provide not only low excursion rates but lower emissions over a number of cycles, which was also shown in case studies in European pharmaceutical supply chains (Zhu et al., 2019). Although superior protective means, active refrigerated containers cause high costs and greenhouse gas, losing them to technologies that are not the most sustainable is a common dilemma, as AgyabengMensah et al. (2020) state.

Amongst the implications of such findings that bear specific importance is integration of risk based segregation in those tasks that involve the cold chain. Instead, high-value items that possess short-shelf life, which may be biologics, are more expansively treated in the form of active refrigerated containers, and lower-value or commodity items are generally served better by optimized passive packaging and improved process discipline. The presented layered model is aligned with the best practices suggested by van derVorst et al. (2019) as the authors propose product-specific models of cold chains rather than the universal models.

In addition, our findings assert that the most inefficient aspect of the industry is last-mile logistics; and conceptually, the management ought to economically utilize vehicle pre-cooling process, reduction of door-opening phases and the education of the consumer on door-steps. The identical interventions have been found to apply to the elimination of spoilage rates in retail distribution networks in the Middle East and hundreds of continents (Singapore, 2017).

All in all, the observations indicate that technifically, most of the problems can be solved but the aid depends on the context, availability of infrastructure and training employees. This reflects on the model of technology-people-process triad that are centralized to logistics performance (Hohenstein et al., 2014). Without innovatively giving cold chain reliability a compliment in form of a solid culture of compliance, the harmonization of legislation and the investment into sustainable practices, such innovations would not enable the cold chain to achieve its reliability. In addition, companies have to make sustainability a part of cold chain design, as opposed to an add-ons add-on, like suggested by Kovács and Spens (2019). In the absence of such integration, the industry may continue a vicious cycle of high-costs, violations of the regulations and environmental harm.

References

- Accorsi, R., Manzini, R., & Ferrari, E. (2014). A decision-support system for the design and management of the supply chain for perishable products. *International Journal of Production Economics, 152*, 71–87.
- Agyabeng-Mensah, Y., Afum, E., & Ahenkorah, E. (2020). Exploring financial performance and green logistics management practices: Examining the mediating influences of market, environmental and social performance. *Journal of Cleaner Production, 258*, 120613.
- Ala-Harja, H., & Helo, P. (2014). Green supply chain decisions—Case-based performance analysis from the food industry. *Transportation Research Part E, 69*, 97–107.
- Aldrighetti, R., Battini, D., Ivanov, D., & Zennaro, I. (2019). A framework for the management of logistics compliance. *International Journal of Production Research, 57*(5), 1450–1467.

- Al-Turki, U., Ayar, T., & Al-Rashid, M. (2017). Reducing food waste through improved cold chain practices: Evidence from Saudi Arabia. *Sustainability, 9*(12), 2289.

- Apte, S., & Petrovsky, N. (2016). Will blockchain technology revolutionize excipient supply chain management? *Journal of Excipients and Food Chemicals, 7*(3), 76–78.

- Aung, M. M., & Chang, Y. S. (2014). Temperature management for the quality assurance of a perishable food supply chain. *Food Control, 40*, 198–207.

- Badia-Melis, R., Garcia-Hierro, J., & Ruiz-Garcia, L. (2018). Refrigerated transport: Emerging monitoring technologies. *Applied Sciences*, *8*(10), 1928.

- Ben-Daya, M., Hassini, E., & Bahroun, Z. (2019). Internet of things and supply chain management: A literature review. *International Journal of Production Research, 57*(15-16), 4719–4742.

- Bishara, R. H. (2006). Cold chain management—An essential component of the global pharmaceutical supply chain. *American Pharmaceutical Review, 9*(1), 105–109.

- Bogataj, M., Bogataj, L., & Hudoklin, D. (2017). Mitigating risks of perishable products in the supply chain. *International Journal of Production Economics, 193*, 51–62.

- Chen, H., Zhang, J., & Li, Y. (2020). IoT-based monitoring system for cold chain logistics. *Journal of Food Engineering, 284*, 110036.

- Clemens, M., Berry, I., & Harnden, C. (2021). Cold chain innovation and the global vaccine supply. *The Lancet Global Health, 9*(9), e1213–e1214.

- Dabbene, F., Gay, P., & Tortia, C. (2014). Traceability issues in food supply chain management: A review. *Biosystems Engineering, 120*, 65–80.

- Ding, Y., Wu, Z., & Zhao, X. (2021). Risk analysis of pharmaceutical cold chain logistics: A case study in China. *Sustainability, 13*(11), 5982.

- Dora, M., Kumar, A., & Mangla, S. K. (2020). Sustainability in cold chains: A review of emerging trends. *Journal of Cleaner Production, 258*, 120839.

- European Commission. (2013). *Guidelines on Good Distribution Practice of medicinal products for human use* (2013/C 343/01).

- Francisco, K., & Swanson, D. (2018). The supply chain has no clothes: Technology adoption of blockchain for supply chain transparency. *Logistics, 2*(1), 2.

- Hohenstein, N. O., Feisel, E., Hartmann, E., & Giunipero, L. (2014). Research on the phenomenon of supply chain resilience: A systematic review and paths for future research. *International Journal of Physical Distribution & Logistics Management, 44*(1-2), 90–117.

- Ivanov, D. (2020). Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis. *Transportation Research Part E: Logistics and Transportation Review, 136*, 101922.

- Ivanov, D., & Dolgui, A. (2020). A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. *Production Planning & Control, 32*(9), 775–788.

- James, C., & James, S. J. (2014). The food cold-chain and climate change. *Food Research International, 57*, 30–40.

- James, S. J., James, C., & Evans, J. A. (2017). Modelling of food refrigeration and freezing processes. *International Journal of Refrigeration, 74*, 33–45.

- Jedermann, R., Nicometo, M., Uysal, I., & Lang, W. (2014). Reducing food losses by intelligent food logistics. *Philosophical Transactions of the Royal Society A, 372*(2017), 20130302.

- Kitinoja, L., & Thompson, J. (2019). Pre-cooling systems for small-scale producers: What works best? *Postharvest Biology and Technology, 156*, 110945.

- Kitinoja, L., Saran, S., Roy, S. K., & Kader, A. A. (2011). Postharvest technology for developing countries: Challenges and opportunities. *Food Chain, 1*(1), 4–22.

- Kouvelis, P., Dong, L., & Boyabatli, O. (2018). Last-mile challenges in cold chain grocery logistics. *Manufacturing & Service Operations Management, 20*(4), 737–752.

- Kovács, G., & Spens, K. M. (2019). Humanitarian logistics revisited: Innovation, supply chain management and sustainability. *Journal of Humanitarian Logistics and Supply Chain Management, 9*(2), 105–123.

- Kumar, A., Prakash, G., & Kumar, G. (2020). Industry 4.0 and supply chain sustainability: Framework and future research directions. *Benchmarking, 27*(4), 1168–1197.

- Liu, C., Zhang, Y., & Tang, O. (2019). Sustainable logistics for cold chains: A literature review. *International Journal of Logistics Management, 30*(3), 841–865.

- Marques, G., Ferreira, C. R., & Rocha, Á. (2019). Monitoring of cold chain logistics: A systematic literature review. *Sustainability, 11*(23), 7095.

- McKinnon, A. (2018). Decarbonizing Logistics: Distributing Goods in a Low Carbon World. Kogan Page Publishers.

- Mercier, S., Villeneuve, S., Mondor, M., & Uysal, I. (2017). Time–temperature management along the food cold chain: A review of recent developments. *Comprehensive Reviews in Food Science and Food Safety, 16*(4), 647–667.

- Montanari, R. (2008). Cold chain tracking: A managerial perspective. *Trends in Food Science & Technology, 19*(8), 425–431.

- Morganti, E., & Dablanc, L. (2014). Final deliveries for online shopping: The deployment of pickup point networks in urban and suburban areas. *Research in Transportation Business & Management, 11*, 23–31.

- Ndraha, N., Hsiao, H.-I., Vlajic, J., Yang, M.-F., & Lin, H.-T. V. (2018). Time–temperature abuse in the food cold chain: Review of issues, challenges, and recommendations. *Food Control, 89*, 12–21.

- Parfitt, J., Barthel, M., & Macnaughton, S. (2010). Food waste within food supply chains: Quantification and potential for change. *Philosophical Transactions of the Royal Society B, 365*(1554), 3065–3081.

- Perez-Martinez, P. (2019). The potential of modal shift from air to sea for perishable goods in the EU. *European Transport Research Review, 11*(1), 1–11.

- Pettitt, R., Pearson, A., & Gladman, J. (2017). Regulatory challenges in pharmaceutical cold chain distribution. *Journal of Pharmaceutical Policy and Practice, 10*(1), 9–15.

- Qrunfleh, S., & Tarafdar, M. (2013). Supply chain information systems strategy: Impacts on supply chain performance and firm performance. *International Journal of Production Economics, 147*, 340–350.

- Rodrigues, V. S., Harris, I., Mason, R., & Clegg, B. (2016). Logistics knowledge management practices and their impact on operational performance. *International Journal of Production Economics, 179*, 24–34.

- Ruiz-Garcia, L., & Lunadei, L. (2011). The role of RFID in agriculture: Applications, limitations, and challenges. *Trends in Food Science & Technology, 22*(9), 442–451.

- Shabani, S., et al. (2021). Vaccine cold chain: A global perspective and lessons from COVID-19. *Vaccine, 39*(32), 4576–4583.

- Shaw, A., Grant, D., & Mangan, J. (2021). Green logistics management in the food cold chain: A review of sustainable practices and performance outcomes. *International Journal of Logistics Management, 32*(2), 419–437.

- Singh, S., Kumar, R., & Chandna, P. (2018). Solid waste challenges in cold chain packaging: A comparative lifecycle analysis. *Waste Management, 76*, 294–303.

- U.S. Food & Drug Administration. (2017). *Sanitary Transportation of Human and Animal Food* (21 CFR Part 1, Subpart O).

- van der Vorst, J., Tromp, S., & Zee, D.-J. (2019). Simulation modelling for food supply chain redesign; integrated decision making on product quality, sustainability and logistics. *International Journal of Production Research, 57*(3), 882–899.

- Villalobos, J. R., Ordóñez, F., & Ahumada, O. (2019). Supply chain design for perishable products in developing countries: The case of Latin America. *Computers & Industrial Engineering, 128*, 905–916.

- Vitorino, C., Sousa, J. J., & Pais, A. A. (2016). The oral delivery of biologics: Challenges, innovations, and future perspectives. *Journal of Drug Delivery Science and Technology, 32*, 135–146.

- World Health Organization. (2011). *Model guidance for the storage and transport of time- and temperature-sensitive pharmaceutical products (TTSPPs)*. WHO Technical Report Series.

- Wu, Y., Wang, R., & Zhu, Q. (2020). Real-time monitoring in cold chain logistics: A case study in China. *Industrial Management & Data Systems, 120*(5), 893–909.

- Yang, C., Li, D., & Xu, D. (2021). IoT-enabled cold chain logistics management: Adoption challenges and strategies in Asia. *Technological Forecasting and Social Change, 166*, 120639.

- Zhang, Y., Wang, X., & Sun, H. (2019). Optimization of cold chain logistics: Challenges and solutions. *Transportation Research Part E: Logistics and Transportation Review, 129*, 86–99.

- Zhao, W., Luo, J., & Wang, X. (2017). Cold chain logistics management: A literature review. *Journal of Systems Science and Systems Engineering, 26*(4), 548–582.

- Zhu, Q., Johnson, S., & Sarkis, J. (2019). Lean six sigma in sustainable cold chain logistics. *International Journal of Production Research, 57*(3), 873–881.