COLD SUPPLY CHAIN AND QUALITY CONTROL IN THE AGRO-ALLIED SECTOR: A LITERATURE REVIEW

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ABSTRACT

The study conducted a systematic literature review on cold supply chain and quality control in the agro-allied sector. The study used 158 selected papers, sourced from Scopus, Web of Science, and authoritative documents published between 2008 and 2026. The study utilised the 2020 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) to ensure transparency and rigour in the identification, screening, and ultimately selection of relevant papers. The extracted data were analysed using thematic synthesis to derive primary trends and emerging themes. The emerging themes identified include real-time temperature monitoring, traceability, cold chain collaboration, and sustainability in cold supply chains. The study revealed that utilising advanced technology for temperature monitoring improves the quality, safety and shelf life of cold chain products. Also, the study revealed that utilising collaborative networks enables increased operational efficiency and reduces operational risks. The study concludes that there is a gradual movement away from traditional refrigeration to the use of the Internet of Things, machine learning, blockchain technology, and phase-change materials. This reflects a general trend toward digitalised and proactive quality control in the cold supply chain. The study identified gaps in the literature and suggested areas for further research on empirical evidence of cold supply chains and quality control in developing countries. The study provides practitioners and policymakers with a sound basis for improving quality control in global cold chains.

Keywords: Agro-allied sector, cold storage infrastructure**,** cold supply chain, product shelf life, quality control

1. INTRODUCTION

Cold supply chain is a critical element of food safety compliance in the global agricultural system. It helps preserve agricultural produce in terms of safety, quality, nutrition from the time the product is harvested until it reaches the final consumer (Mustafa, Navaranjan & Demirovic, 2024). In recent years, academic research and industry application of cold supply chains have increased significantly. This portends that cold supply chain is increasingly contribute to global food security (Mustafa et al., 2024). Cold supply chain consists of several key technologies, including refrigerated warehouses, thermal insulated containers for transport, real-time temperature monitoring and tracking systems, and traceability systems. These technologies work together to prevent microbial growth and spoilage, which are the primary objectives of maintaining products freshness/safe during transport (Awe, Ekpudu & Sulaimon, 2024; Badia-Melis, Ruiz-Garcia, & Robla-Villalba, 2023). Badia Melis et al (2023) pointed out that whenever an environment that keeps the products within the cold chain is compromised, the product's quality/freshness will degrade immediately from that point. This reinforcing the critical connection between the performance of the cold chain and the quality of the product.

Global studies have shown that maintaining the temperature of perishables throughout the cold chain will prolong their shelf life and significantly decrease losses after harvest. This is a significant approach for assuring quality control in developed nations where there are many markets for perishables. For example, integrated cold chain management through the use of advanced technologies and collaborative logistics improves the food safety and regulatory compliance provisions available to the United States, Europe, and East Asia. In this countries, old chain performance is dependent on quality assurance requirements based on the enforcement of standards set forth by such agencies as the Food and Drugs Administration (FDA) and European Food Safety Authority (EFSA). Recent study has identified a number of research clusters dedicated to food safety, sustainability, and efficiency of cold chain systems as shown by technological innovations (Han, Sun, Ji & Yang, 2025).

Studies advanced economies further illustrates the causal pathway between cold chain effectiveness and quality outcomes. Ren, Fang, Yang, and Han (2022) show that technologies such as Internet of Thing (IoT) sensors and adaptive systems can transition cold logistics from reactive to proactive models that anticipate and mitigate quality risks before deterioration occurs. This evolution reflects the view of Zhong (2023), who argued that the synergy between cold chain logistics and quality control is enhanced in digitally enabled systems that provide continuous environmental monitoring.

While there have been many global advances in cold supply chains, many developing countries – and specifically in Africa – lack a developed cold supply chain. This has resulted in a poor ability to translate cold supply chain performance into consistent quality control. Study in Nigeria's agricultural value chain has shown that insufficient refrigerated storage, fragented logistics systems and unreliable power sourcing impede the ability to maintain proper temperature management. This led to large losses of products post-harvest and weakening the ability to provide quality assurance. To support this finding, AbduGhani, and Mokhtar (2024); Zego, Mohamad Husny Hamid, revealed that nearly 50% of Nigeria's tomatoes lost in a year due to insufficient cold logistics operations. Hence, quality assurance was compromised at various points throughout the supply chain.

The review of extant studies shows that the establishment of cold chain operations is hampered by persistent challenges resulting from fragmented infrastructure, high operating costs, and

limited technical knowledge. These issues affect the overall impact cold chain systems may have in ensuring quality control of perishable goods within the sub-Saharan region of Africa. Zhang and Mohammad (2024) indicated three common challenges inhibiting the successful preservation of food quality and the overall resilience of the cold chain system during unexpected disruptions (COVID-19 pandemic). This includes energy consumption, workforce skills gap and regulatory concerns regarding sustainability. In the same vein, Arriaga Lorenzo et al. (2023) revealed that the significance of cold chain systems is a part of a wide range of food safety concerns that have direct consequences on greenhouse gases and foodborne diseases. These strands of studies provide a coherent, evidence-based study that demonstrates the relevant of cold supply chain in determining the quality control of perishables.

2. LITERATURE REVIEW

2.1 Theoretical Review

2.1.1 Resource-Based View Theory

Wernerfelt (1984) and Barney (1991), the proponents of Resource-Based View (RBV) asserted that RBV relates to the way firms create value through their internal (rather than external) resources and capabilities. The RBV has a broad definition of Resources. Resources include more than just physical assets; they also include technological systems, organizational processes, managerial capability and human expertise (Barney, 1991; Wernerfelt, 1984). Therefore, in the agro-allied industry, components of cold supply chain can be classified as strategic resources that are embedded within the firms and across the supply chain (Christopher, 2023). Cold supply chain resources are valuable because, among other things, they provide the means for an agro-allied firm to manage product perishability and limit the effects of environmental and handling risk. This helps the firm in maintaining product freshness and quality (Teece, Pisano & Shuen, 1997; Oakland, 2023). In many developing Countries, cold supply chain resources may be rare due to their high capital costs, technological complexity and infrastructure limitations (Teece, 2018). The RBV helps explain how differences in the quantity/quality of cold supply chain resources provides variation in quality control capability between agro-allied supply chains. Hence, the RBV provides a stable theoretical foundation to support the study

2.2 Conceptual Review

2.2.1 Cold Supply Chain

Recent studies have recognised cold supply chain as an advanced logistics system that applies technology to facilitate the quality/freshness of perishables from the point of harvest to the final consumers. In developed countries, where food safety regulation and quality consistency are highly regulated, cold supply chain is considered to be more than simply a basic infrastructure for physical transport. It is also considered to be a data-driven system that incorporates the monitoring of temperature, humidity, and other product handling metrics over multiple supply chain stages. (Elashmawy, Doron, Kanjilal, Brecht & Uysal, 2025; Protopappas, 2025). Thus, cold supply chain is conceptualised as the operational extension of quality assurance, rather than as simply another logistics function to perform.

Globally, cold chain technology is making significant advancements in using sensor technology in every aspect of the cold chain, from transportation through storage. This allows producers to receive real-time environmental monitoring and early alerts about any deviations

that could negatively affect the quality of their product. The experience of the North America and Europe suggest that by using digital cold chain models, cold chain gain greater visibility and responsiveness. This allows quality issues to be addressed during transit instead of upon delivery (Elashmawy et al., 2025). The shift towards using continuous data streams as a basis for decision-making in the supply chain conveys a movement from using inspections at the point of manufacture/packaging to taking a process-based approach to quality control.

Recent study shows how IoT will help businesses improve cold chain coordination, as IoT is a key enabler of cold stores. It has been demonstrated that when agro-allied firms use IoT-enabled systems to monitor temperature/humidity, they can increase traceability and improve compliance with food safety regulations. This is because the monitoring capabilities provide a comprehensive record of the conditions in which products were handled (Protopappas, 2025). The technology also has been used for the development of quality control via the ability to provide factual evidence of appropriate handling conditions. This supports greater accountability among all supply chain players. On a more conceptual basis, traceability is becoming increasingly tied to logistics performance and consumer confidence from a regulatory standpoint.

Using blockchain in temperature-controlled supply chains has developed a plethora of opportunities to examine both the quality assurance and transparency in cold chain. Studies indicate that a combination of IoT sensors and blockchain based architectures can allow all supply chain parties to share their data in an immutable manner. This would decrease information asymmetry and enhance the quality assurance in perishable food supply chain (Kandasamy, Halder & Rahman, 2025; Villegas-Ch, Gutiérrez, Govea & García-Ortiz, 2025). The operating context for these systems is that, in an advanced country, they are usually referred to as "decentralised quality control" as opposed to being centralised to a single entity. This perspective supports collaborative quality control in cold chain along with collaborative supply chain models, data integrity. and co-responsibility for quality outcomes.

Sustainability has become a major focus of many studies related to cold supply chain in today's society. Studies have shown that energy requirements associated with refrigeration create issues when trying to minimize food waste and food loss. Recent studies indicated that while cold supply chains achieve sustainability goals by extending shelf-life and decreasing spoilage, they also create potential issues in terms of energy use and carbon emissions (Alherimi, Alzahrani, Alqahtani & Alshahrani, 2025). As such, there is an increasing number of research conducted to develop optimal designs for cold chain that create an optimal balance between food quality preservation and environmental performance.

2.2.2 Quality Control

The quality control of agricultural products has been defined as the processes and procedures in place to ensure that the product meets specified safety and quality standards from the time of its production through its processing and its eventual distribution (Plakantara & Karakitsiou, 2025). The traditional or limited understanding of quality control has been to inspect the product at the time of packaging before it is delivered to the consumer. However, quality control has been identified as being part of the wide supply chain (Plakantara & Karakitsiou, 2025). The quality control within the global agro-allied supply chains is not solely considered as compliance function. It is also a risk management system that can directly affect the consumers health, market access and the overall financial success of agribusinesses.

Quality control is not just about reacting to quality issues in the cold chain. Instead, it is about preventing quality issues from occurring through risk assessment and mitigation strategies.

There are many ways biological, chemical, and operational risks can make their way through cold chain. When these risks exist in the cold chain, they can affect the products safety, economic performance and sustainability of the products. Study has suggested using intelligent decision systems with risk indicators to help predict quality failures where there are significant microbial risks. Therefore, the study highlights that quality control occurs at the intersection of hazard identification, cold chain resilience, and strategic thinking/decision-making. (Plakantara & Karakitsiou, 2025).

2.3 Empirical Review

Across the literature, studies have consistently highlighted the importance of maintaining proper temperature control as an essential factor in maintaining the quality of products. Some of the studies revealed that a small amount of deviation from the required temperature range will greatly increase biochemical degradation, microbial growth, and loss of quality for perishable foods (Aung and Chang, 2014; Mercier Villeneuve, Mondor & Uysal, 2017; Ren et al., 2022). Supporting evidence shows that temperature abuse has continued to be an issue, even with advancements in refrigeration technologies, especially throughout the transportation or last mile distribution process (Badia Melis et al., 2023; Mustafa et al., 2024). Conversely, studies have revealed that the static temperature settings are often not adequate in dynamic logistics environments. The studies revealed a transition from static temperature controls to adaptive and stochastic controls that are adjusted based on real-time operational conditions (Giliberto, Paradiso & Wozabal, 2025; Hwang, Rhee & Lee, 2025). It was further revealed that the implementation of adaptive/stochastic controls helps retained quality and minimised spoilage.

Recent studies have revealed digital monitoring technology as an approach of facilitating quality assurance across cold chain operations. It was revealed that technologies such as embedded IoT sensors, flexible temperature sensors, and time/temperature indicators help to identify deviations from acceptable ranges early enough to take corrective actions and avoid loss of quality (Cil, Abdurahman & Cil, 2022; Waldhans, Albrecht, Ibald, Wollenweber, Sy & Kreyenschmidt 2024; Wang et al., 2023). More recent studies further extended the capabilities of these systems through the application of artificial intelligence and machine learning for predictive shelf-life determination and optimisation of product handling decisions (Elashmawy et al., 2025; Liakos, Athanasiadis, Bozinou & Lalas, 2025). Badia-Melis, Mc Carthy, Ruiz-Garcia, Garcia-Hierro, and Robla-Villalba (2018) contradicts the findings and revealed that no single monitoring temperature technology solves every cold chain issues and revealed inefficiencies in cold chain system.

In cold supply chains, the complementary aspects of quality control are traceability and visibility of information. Studies have established how fragmentation of information flows results in quality degradation as a result of the lack of accountability among supply chain actors (Kankam, Kyeremeh, Som & Chanor, 2023; Trienekens & Zuurbier, 2008). In contrast, Duman and Aydoğan, (2025); Uyar, Papanikolaou, Kapassa, Touloupos, and Rizou (2025); Zayed and Yaseen, (2025) revealed that blockchain-based traceability systems facilitate temperature integrity and data transparency in the cold chain.In line with the finding, Parvaiz, Dedahanov, Abdurazzakov, and Rakhmonov (2022); Plakantara and Karakitsiou (2025) revealed that these systems enhance compliance with safety/quality standards, build stakeholder confidence and allow for faster root-cause analysis of quality failures. However, the studies identify barriers to creating interoperable systems, cost and readiness of organisations to implement these systems, particularly in developing country contexts.

There is an additional significant area of research that connects quality control with collaboration and integration within the supply chain. Studies have shown that the level of trust and collaboration among producers, logistics service providers, and retailers significantly influence quality control (Dubey et al., 2017; Zarei, Rasti-Barzoki, Altmann & Egger, 2023). Han, Huang, Hughes, and Zhang (2021) contradicts the finding and revealed that high level of trust may lead to complacency and reduced monitoring, ultimately affecting quality outcomes. However, recent studies revealed that collaborative networks promote joint problem-solving, standardised handling procedures, and quality consistency (Alsmairat, Al-Ma'aitah, Al-hwameil & Elrehail,2024; Alzate Rendón, Álvarez Gallo & Boada, 2025). These relational mechanisms are increasingly viewed through the lens of dynamic capabilities, which refers to how well cold chain players can sense, seize, and reconfigure its resources. This will enable them to respond to temperature excursions, demand fluctuations and disruptions in the chain without compromising its quality.

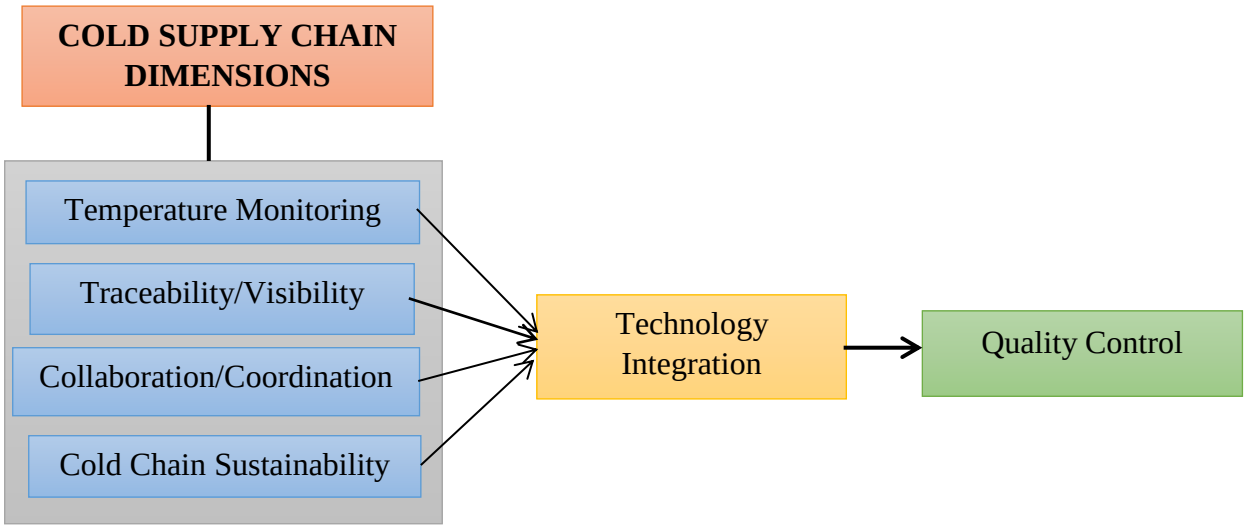
Sustainability issues extend the conversation about cold supply chain and quality control and create new areas for future research. There is a great deal of study on the relationship between maintaining product quality, waste reduction and improving product's environmental performance; (Wang, Chan, Kumar & Tsolakis 2024; Wu, Marson, Fedele, Scipioni & Manzardo 2022). The studies revealed that when products are wasted due to spoilage, both economic and carbon emissions loss occur. However, studies have revealed that energy-efficient refrigeration systems, phase change materials, and optimally routed transportation will improve both the retention of product quality and decrease the overall environmental impact (Calati, Hooman & Mancin, 2022; Chen, Zhang & Zhang, 2024; Mohan & Amin, 2025). However, contrasting findings indicate that the ability of sustainable cold chain technologies to enhance product quality is highly contingent on factors such as cost structures, technological compatibility, infrastructure quality, and operational discipline (Chen & Zhang, 2024; Shahzad, Ali & Li, 2026).

Studies in developing countries provide insightful information about structural limitations impacting cold chain quality assurance in developing countries. Study from Nigeria, Kenya, Tanzania and India show that inadequate infrastructure, insufficient access to cold storage and refrigerated transport, as well as insufficient skilled-personnel are the primary contributors to post-harvest waste and quality loss (Ndilibango, Musabila, & Nsimbila; Roy, 2025; Zego et al., 2024). In the same vein, reports from industry and policy analyses provide evidence of the level of unmet demand for cold storage solutions and their effect on food quality and safety (BusinessDay NG, 2025; Guardian Nigeria, 2025; TraceData Research, 2025). However, innovative business models and investments made by private companies using modular cold storage solution might eradicate product spoilage in agro-allied cold chain in developing countries by providing improved quality in supply chains connected to small farmers (ColdHubs Ltd, 2023).

There is a general consensus in different sector (food, pharmaceutical and vaccine) that effective and efficient cold chain system plays a significant role in quality control of perishables. In the instance of pharmaceuticals and/or healthcare cold chain, the study states that improperly monitoring temperature or lack of sufficient coordination would negatively affect product efficacy and patient safety and establishes) a clear alignment between Food Systems (Girma et al, 2024; Potters, Nezhad, Bernard, Hans & Asadi, 2024; Turan & Ozturkoglu, 2022). Also, the study shows that cold chain processes are significantly an information-intensive, capability-driven function characterised by the interaction of temperature management technologies, digital traceability, organisation collaboration, and supporting infrastructure

2.4 Conceptual Framework

A conceptual framework is designed for the study based on the review



Source: Researcher (2026)

Figure 1: Conceptual framework for cold supply chain and quality control.

3. METHODOLOGY

The study used a systematic literature review design supported by PRISMA 2020. The study used 158 selected papers. The papers were sourced from Scopus, Web of Science, and authoritative documents published between 2008 and 2026. The used PRISMA framework to guarantee transparency and rigor in the identification, screening, and ultimately selection of relevant papers. The PRISMA flow is summarised in the table below:

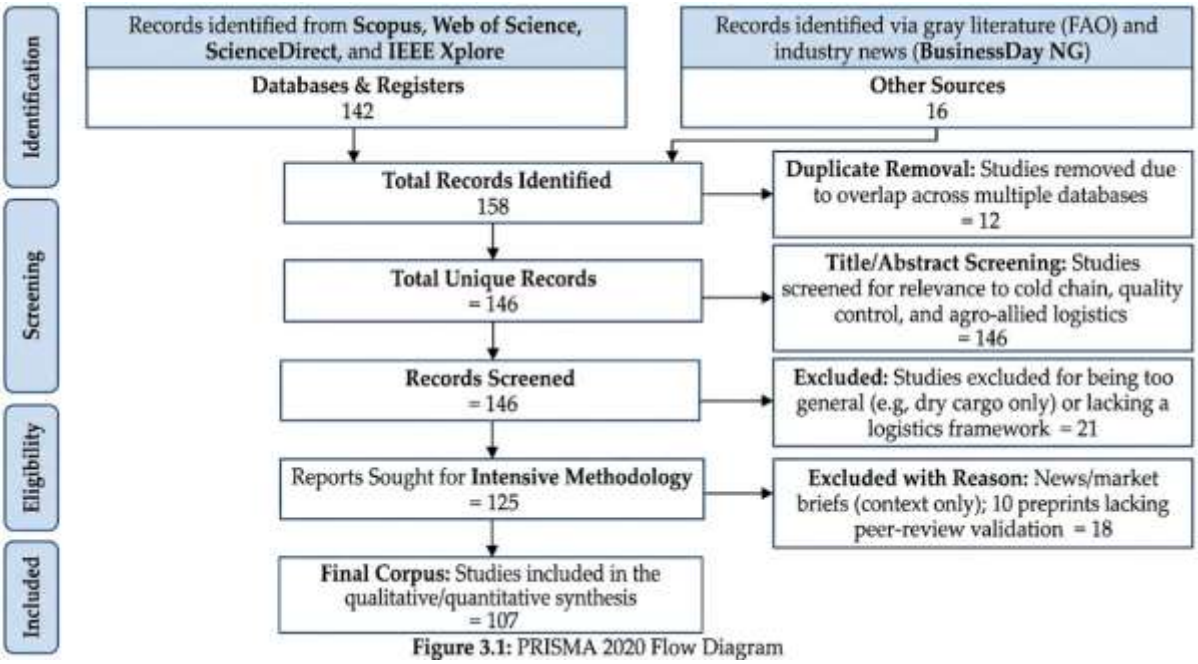


Figure 3.1: PRISMA 2020 Flow Diagram

As revealed in Table 3.1, the study used 107 studies for the final thematic synthesis. The data extracte were analysed using both descriptive and thematic synthesis to derive the primary trends and emerging themes from the data. The extraction process revealed several research gaps related to temperature monitoring, traceability, collaborative operations, and sustainability issues in cold chain.

4. ANALYSIS

4.1 Thematic Analysis

As shown in the PRISMA flow diagram, 107 studies were reviewed for trends; geographic location; type of publication; and primary area of emphasis in their research.

4.1.1 Temporal Evolution and Research Trends

The study revealed that approximately 65% of the studies on cold supply chain were published in 2023 and 2024, demonstrating a recent emphasis on the development and implementation of new technology solutions, and sustainability. Most of the remaining 35% of studies are foundational or earlier(s) in nature and provide the theoretical and methodological insight in cold supply chains and quality control.

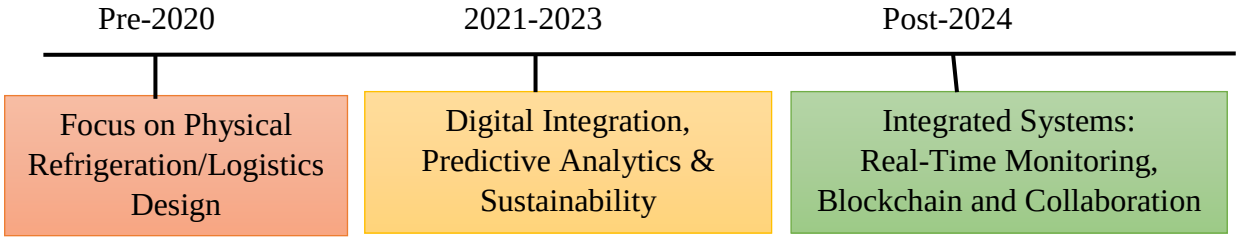


Figure1; Evolutionary Roadmap of Cold Chain Research Focus

As seen in figure 1, the study revealed that pre-2020 studies largely focused on physical refrigeration and logistics design. 2021-2023 focused on digital integration, predictive analytics and sustainability. However, there is significant movement post-2024 towards integrated systems that have real-time monitoring, blockchain traceability and collaborative governance of a proactive and data driven approach to quality control.

4.2 Publication Patterns and Disciplinary Spread

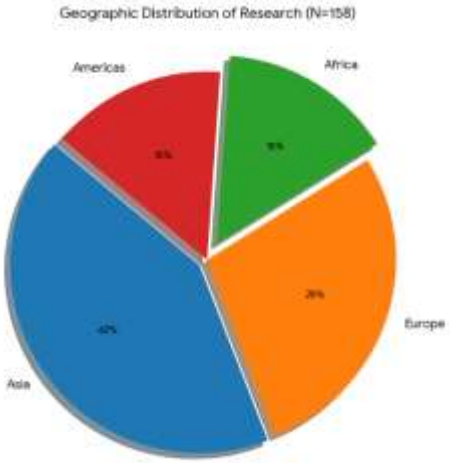
Table 4.1 Publication Patterns

Publication Type	Percentage (%)	Primary Role in Study
Journal Articles	56	Providing core empirical data and validated methodologies.
Conference Papers	20	Early-stage reporting on IoT and AI pilot simulations.
Reports/Policy Documents	12	Contextualizing the investment gap (FAO, World Bank).
Preprints/Grey Literature	12	Real-time market updates and news (e.g., *BusinessDay NG*).

Source: Researcher 2026

The review of the literature is quantitatively characterised by their respective reference types. As revealed in Table 4.1 above, 56% were journal articles, 20% were conference papers, 12% were reports or policy documents, and 12% were preprints or grey literature. This indicates that journal articles have generated significant academic effort in this area. There is a reliance on these alternative formats in order to monitor the development of new technologies in cold supply chains using emerging digital technologies. The journals that published most of the studies reviewed include: Food Control, Sustainability, Trends in Food Science & Technology, and Applied Sciences. The journals reflect the cross-disciplinary nature of the study in cold supply chain, including food safety, logistics, and digital innovation.

4.1.2 Geographic Distribution and Contextual Differences



Regional Research Paradigms

Region	Primary Research Emphasis
Africa	• Infrastructure Gaps • Market Readiness • Contextual Quality Control
Asia & Europe	• IoT & AI Implementation • Blockchain Traceability • Phase Change Materials (PCM)

Figure 2: Geographic Distribution

As revealed in figure 2 above, the 42% of studies reviewed were conducted in Asia, 28% were conducted in Europe, 15% were conducted in Africa, and 15% were conducted in North and South America. It was revealed that the studies conducted in Africa tend to provide a contextual basis for cold supply chain The studies focused primarily on the infrastructure gap and the levels of development and market readiness in Africa (BusinessDay NG, 2025; Maganga, 2025; Zego et al., 2024). Studies in the African region primarily focus on limiting factors and deficiencies within the existing system, which hinders the proper implementation of an effective cold chain.

This implies that studies on cold supply chain and quality control are still in an early state of research development. Their aim is to identify and address structural barriers to the successful adoption of cold supply chains in the agro-allied sector. However, studies conducted in Asia and Europe focused largely on technological solutions in cold chain, which including blockchain, IoT, AI, and phase change materials (Chen et al., 2024; Elashmawy et al., 2025; Giliberto et al., 2025; Protopappas, 2025). This revealed that the regions have gone beyond adopting basic infrastructures and have transitioned to developing optimizations for their cold chain operations, enhancing their efficiencies and integrating their cold chain systems. The presence of technologies in these regions demonstrates a high degree of digital readiness, institutional support and investment in cold chain innovation.

4.1.3 Thematic Prevalence in Cold Chain Research

Table 4.2 Theme Prevalence

Research Theme	Prevalence (%)	Estimated Count (n)	Key Focus Areas
Temperature Monitoring	68	107	Maintaining high quality through rigorous monitoring.
Traceability /Visibility	54	85	Use of Blockchain and IoT for real-time data trails.
Coordination /Collaboration	41	65	Alignment, partnerships, and governance mechanisms.
Sustainability/Waste Reduction	38	60	Reducing environmental and economic impacts.

Source: Researcher 2026

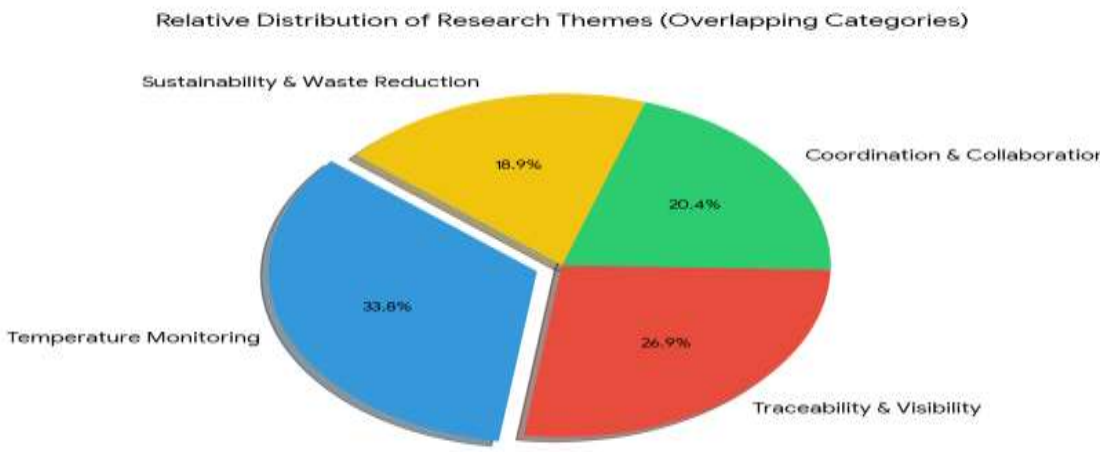


Figure 3: Relative Distribution of Research Theme

Temperature is the area most studied, being present in 68% of the studies reviewed on this subject matter (Aung & Chang, 2014; Perler et al., 2026; Waldhans et al., 2024). Traceability and visibility of information occurred in 54% of the papers, primarily with regard to the use of blockchain technology or internet-of-things technology as an enabling platform (Duman & Aydogan, 2025; Uyar et al., 2025; Villegas-Ch et al., 2025). The next largest category of themes represented in the literature consisted of coordination/collaboration. It appears in 41% of the reviewed and focused on the importance of establishing mechanisms for oversight/governance, partnerships, joint efforts, and aligning the supply chain as what's needed to achieve quality control (Alzate Rendón et al., 2025; Susanto et al., 2023; Zarei et al., 2023). The final key theme reported in the studies is sustainability and waste reduction, appears in 38% of the papers reviewed. It indicated that the effectiveness of the cold chain system has a direct correlation to both the environment and the economy (Abbas, Zhao, Gong & Faiz, 2023; Mohan & Amin, 2025; Zhang & Mohammad, 2024).

The study indicates that the cold chain field has become a technologically integrated, information-based, and collaborative system. It is revealed that temperature control is still the basis of cold supply chain in maintaining quality control in agro-allied sector. However, real-time monitoring, traceability of supply chain data, and visibility into all supply chain information largely determine the effectiveness of temperature control. The reinforcement of these digital capabilities depends on coordination/collaboration between supply chain actors to provide conformity, accountability, and governance in the cold chain. Sustainability and waste reduction are both product outputs and business outcomes, as well as motives for linking operational efficiency and environmental/economic performance.

These dimensions of cold supply chains identified are interconnected. They create an interrelated feedback loop through which quality control is enhanced in the cold chain. Given the to technological advances in cold chain as identifies in advanced countries, adoption gaps persist, especially in developing countries. This highlights the need for context-specific solutions and empirical validation.

4.1.4 Technology Adoption and Innovation Patterns

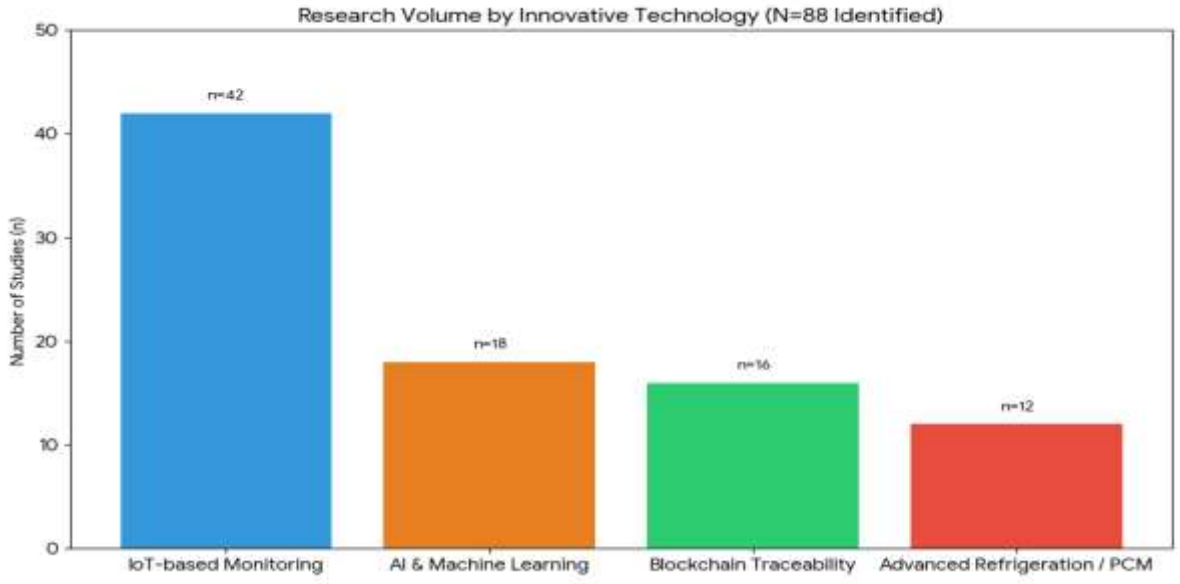


Figure 4: Research Volume by Innovative Technology

The Figure 4 above shows the thematic analysis through technology adoption and innovation pattern. The study revealed that IoT-based monitoring was the most researched innovative technology (n=42) with only AI and machine learning for predictive QC (n=18), blockchain-based traceability (n=16) and advanced refrigeration or PCM (phase changing material) (n=12) being the next most researched. The most researched form of implementation was conceptual research followed by simulation-based research with very little empirical research done at pilot scale on IoT adoption. The gap in adoption of IoT was more pronounced in developing nations due to repeated citations of high costs, limited digital infrastructure and human capital deficits (Maganga, 2025; Ndilibango et al., 2025; Zego et al., 2024).

Despite the growing interest in cold chain, majority of the studies conducted are either conceptual or simulation-based. This shows little empirical evidence from either pilot or industrial applications. This portends a gap between theoretical advancement and practical

application. Also, challenges to cold chain adoption are highly pronounced in developing regions, where poor digital infrastructure, high costs, and lack of trained personnel constrain the adoption of advanced cold chain technologies.

Collectively, the information provided through the thematic analysis revealed that the effective management of cold supply chains is reliant upon the concurrent progression of three key conditions: real-time temperature-monitoring systems, traceability and visibility of information, and the establishment of collaborative networks for governance of cold supply chain operations. Furthermore, the analysis reveals regional variations in cold supply chain technology adoption, gaps in cold supply chain technology adoption. The study also revealed the need for more research and empirical data on the practical application of the three pillars of effective cold supply chain management.

4.2 Discussion of Findings

The thematic analysis shows that temperature management is still the most important factor of cold supply chain management in the agro-allied sector. Its significance emphasizes how critical it is to maintain product integrity, product safety and regulatory compliance. However, findings suggest that the way temperature management is viewed has changed. It is no longer considered independently but has been integrated into real-time monitoring technologies and digital tools to support temperature management. This change indicates that temperature management could not exist without other systems that complement temperature management and contribute to both timing and data accuracy.

Traceability and visibility of information were also noted as major themes in the literature. The integration of technologies (blockchain and IoT) provide support for enhanced tracking and visibility of product movement through the supply chain. This provides transparency, accountability and better decision-making capabilities in the cold chain. Therefore, players in the supply chain will have better opportunities to detect and respond to potential supply chain disruptions. Evidence from the thematic analysis suggests that traceability will play an increasingly important role in the development of modern cold supply chains. As a result, cold supply chains will become data-driven systems that facilitate proactive management versus reactive management.

An additional theme identified involves coordination/collaboration established among various in stakeholders in cold chains. It was recognised that poor coordination within the cold supply chain will produce inefficiencies, delays, and substandard product quality. Conversely, effective collaboration within a cold supply chain will lead to a higher degree of alignment and enhance the quality performance of the cold supply chain. This demonstrates that cold supply chains are not only technology-based systems; they also depend on governmental and cooperative support as social and organizational networks.

The analysis identified sustainability and waste reduction as outcomes of effective cold supply chain. The study indicates that effective quality management leads to the reduction of food waste, reduced energy usage, and improved environmental performance. Simultaneously, the increased attention sustainability has encouraged the adoption of technology that conserves the operating environment and promotes product safety.

5. CONCLUSION

The study shows that there are three main components of a cold supply chain that will facilitate quality control of perishables in the agro-allied sector. The first pillar is the use of real-time temperature monitoring and control. Most of the studies presented focused on temperature monitoring (real-time). The study revealed that it is one of the most important ways to maintain product quality in cold supply chains. The second pillar is generally be inferred as traceability, primarily enabled by the implementation of blockchain and IoT. It is an important component in assuring accountability and regulatory compliance. The third pillar revolves around coordination and collaboration among key player in the cold chain. This help to facilitate quality control and mitigate the risks associated with fragmented (poorly integrated) cold chain networks. There is also a developing trend toward incorporating sustainability and waste reduction into research trend, and connecting cold chain efficiency with positive environmental/economic impacts. As such, there is a gradual movement away from traditional refrigeration to the use of IoT, Artificial Intelligence (AI), machine learning, blockchain technology, and phase-change materials. This reflects a general trend toward digitalised and proactive quality management in the cold supply chain.

5.1 Practical Implication

To enhance quality control in the agro-allied cold chain will require the key players to adopt IoT-enabled real-time temperature tracking systems. This will invariably guarantee the safety and shelf life of perishables. There is an urgent need to solidify the coordination among cold chain players in developing countries, particularly in Nigeria. Doing so will curtail the inefficiencies posed by fragmentation in the cold chain. Also, the study shows that there is an urgent need for investment in digital infrastructure, capacity building, and collaborative frameworks in Nigeria agro-allied sector. Doing so will increase the efficiency, transparency, and sustainability of cold supply chains to optimizing quality control.

5.2 Gaps and Suggestions for Further Studies

Many gaps still exist in both supply chains and digital technologies. The limited empirical studies on this subject area raises concerns. Most recent studies conducted can be described as either conceptual in nature, simulation-based, or pilot scale studies. In addition, other gaps include lack of empirical validation of cold supply chain innovations within the context of developing nations. Furthermore, there are many available technological solutions used within cold supply chain today that have not been systematically evaluated with regards to efficiency and sustainability metrics throughout the cold chain.

Potential future research should conduct longitudinal and empirical studies for the purpose of validating the proposed digital monitoring, traceability, and collaboration frameworks within developing nations. Future studies should identify cost-friendly methods for adopting emerging technologies. They should develop cross-regional benchmarks through the comparative analysis of emerging and advanced nations. This will help to create a definitive set of best practices with regards to technological innovations and collaborative technologies within cold chain systems.

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