

Waste minimization in food cold chain using Industry 5.0: Review

Focus on Artificial Intelligence

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Abstract

A special style of supply chain management, known as cold chain, has grown in popularity during the last two decades. This could be credited to an assortment of variables like changing social structures, consumer tastes, and a rise in the working population. Food waste, a worldwide issue and inefficiencies in cold chain being one of the major cause of losses, are certainly critical issues specifically in nations that are yet in developing phase. The study stress upon the possibility and urgent need to recuperate cold chain operative efficiency through utilization of Industry 5.0. Enhanced human-machine cooperations will result in more effective decision-making; encourage upon circular economy and sustainability, all being aligned with the objectives of global climate management. By methodically examining previous studies, the review also closes a vacuum in the literature by providing a cohesive picture of current trends, difficulties and potential path forward.

The study uses bibliometric analysis data to show how research in the cold chain sector has changed globally over the last 21 years. The study also includes a review tool, SPAR-4 for conducting a systematic literature review. These findings not only confirm what other researchers have found, but also reveal new trends that could lead to exciting research and policymaking opportunities in the cold chain. According to the study, cold chain, AI, and ML have become more important starting in 2020. Technical developments, a better awareness of global health issues, and environmental concerns are the main causes of the increased emphasis on research and development in the field of cold chain management. A map of networked co-authorship and co-citations was also created by this study, showing how people work together, highlighting important contributions, and highlighting research areas that have a big influence on the field.

Keywords Cold Chain, AI, Artificial Intelligence, Information Technology, Bibliometric Analysis, SPAR-4

1. Introduction

The preservation of attributes and safety of foodstuff depends upon food chain which comprises numerous commodities that are perishable in nature hence requiring appropriate storage, transportation and refrigeration. Waste in the cold chain persists despite technological developments owing to inefficiencies, lack of real-time monitoring and inadequate control and coordination [1][2][3]. By coalescing human knowledge with technologies namely, AI (artificial intelligence), robotics, etc., fifth industrial revolution promotes an archetype change thereby focussing on human-centered, sustainable-cum-resilient systems. This study which aims to investigate how Industry 5.0 might revolutionize waste management in food cold chain considers the nexus of technical innovation and sustainability.

In the face of growing demand, resource constraints, and climatic unpredictability, universally food chain is under increasing pressure to develop upon sustainability, cut waste, and recuperate. The food cold chain, which handles perishable commodities that need exact temperature control from manufacture to consumption [4], is one of its most vulnerable sectors. Almost 15% of food loss worldwide is caused by inefficiencies in this chain, which exacerbates financial and environmental consequences [5]. These inefficiencies include inadequate inventory management, temperature swings, and logistical delays. Industry 5.0 incorporates human-centricity, sustainability, and resilience into technical innovation distinct from its predecessor, Industry 4.0, that put an emphasis on computerization and data-driven competence with utilisation of trailblazing technologies like blockchain, digital twins, AI, IoT (internet of things) and cobots (collaborative robotics) to build systems that are intelligent, flexible, and socially conscious [1][6][7].

Industry 5.0 technologies have the ability to completely transform food cold chain processes, as evidenced by recent research. For example, demand forecasting accuracy has been demonstrated by predictive analytics models such as ARIMA and Multiple Linear Regression (MLR) [8] which allow for improved inventory control and less waste. Real-time temperature and humidity monitoring is made possible by IoT-enabled sensors, while supply chain transparency and traceability are guaranteed by blockchain technology. In addition to reducing waste, these solutions support Sustainable Development Goal 12.3, which demands clipping into half the global food loss and waste by 2030 [9]. Use of Industry 5.0 to food cold chain waste control is still poorly understood, despite increased interest. The literature that is now available is dispersed and frequently concentrates on discrete technologies or particular phases of the supply chain. To map recent developments, pinpoint research gaps, and suggest integrated frameworks for waste minimization, a thorough synthesis is required which the study aims to conduct.

2. Review of Literature

2.1 Cold chain and waste minimization

With faster reaction times, the food business is becoming more and more customer-focused. A cold chain that can deliver food items, particularly perishables, faster and with better quality might be viewed as a strategic advantage. In order to maintain integrity of food chain, safety and quality are crucial in the increasingly globalized food trade. The food supply chain (SC) must provide sufficient information about food characteristics, source, classification of problems in Indian frozen food CC (cold chain) and environmental needs [10][11]. There is a need for coordinated research that considers temperature control, food waste, distribution management, CO₂ emissions, and energy use. Economic, environmental, and societal issues must be observed and resolved to overcome obstacles facing food SC.

Food waste occurs when food quality deteriorates to the point where it is thrown out by cold chain participants [12][13]. Inadequate training of cold chain operators results in inadequate awareness and handling procedures [14][15][16] which is a main cause of food loss and waste. Consequently, cold chain has emerged as a crucial necessity for sustaining quality and safety of frozen food in light of shifting consumer tastes and preferences as well as changing lifestyles. Reducing food losses and waste may be possible with the identification of these problems.

2.2 Industry 5.0 and its role in waste minimization

Industry 5.0, also known as the fifth industrial age, stresses upon the synergy between innovative technological solutions and human creativity. Built upon the groundwork of industry 4.0, it blends cutting-edge technology with industrial processes, such as robotics, big data analytics, artificial intelligence (AI), the Internet of Things (IoT), and cyber-physical systems with human-centric values such as personalization, resilience and sustainability. This paradigm shift endorses collaborative interaction between humans and technologies, enabling more customized, ethical, and environmentally conscious production. Industry 5.0 fosters a balanced ecosystem where innovation is driven not only by efficiency and automation but also by social responsibility and meaningful human contribution.

The reduction of waste throughout the value chain is one of Industry 5.0's primary contributions. Industries can track machine performance, raw material usage, and energy consumption in real time with IoT-enabled sensors and data analytics [17][18]. While digital twins and simulation tools enable businesses to optimize production prior to real deployment, hence eliminating trial-and-error waste, predictive maintenance minimizes downtime [19][20]. By following these procedures, production errors are greatly decreased and resources are employed effectively.

Additionally, by facilitating improved material and product tracking through technologies like blockchain and smart tagging, Industry 5.0 promotes circular economy practices [21]. In addition to tracking product life cycles and recovering valuable resources at the end of usage, manufacturers can design for recyclability [22]. Sorting and recycling procedures are also made more efficient by automation and robotics, which lowers human error and improves waste management effectiveness. Demand and supply are better coordinated in supply chains thanks to improved analytics and AI-driven forecasts [23][24] which also minimize overproduction and inventory waste.

Industry 5.0 turns waste management into a proactive approach rather than a reactive one. Organizations can save costs, improve competitiveness, and lessen their environmental impact by integrating sustainability into the very fabric of cold chain operations. Waste reduction is now a strategic result of intelligent, networked, and sustainable manufacturing systems driven by Industry 5.0 human-cum-technology combination rather than simply a byproduct of efficient production.

3. Methodology

Study design, information sources and literature search

A Boolean search strategy was applied using combinations of keywords such as: ("AI" or "artificial intelligence") and ("cold chain" or "cold supply chain"). The Scopus database was accessed for extracting the requisite data, chosen due to its broad coverage of multidisciplinary research in emerging technologies, sustainability, and supply chain management. SPAR-4 (Scientific Procedures and Rationales for Systematic Literature Reviews) was used as a tool for depicting the systematic literature review process. The review study employed bibliometric mapping technique with the help of software such as VOSviewer and RStudio. The process analysis included descriptive analysis of trends in publication, types of publication, keyword occurrence analysis.

Research questions

The purpose of this systematic LR study is to:

- Investigate how Industry 5.0 technologies contribute to waste reduction
- Determine the key success criteria
- Make recommendations for future research directions to develop cold chain systems that are human-centered, sustainable, and resilient.

Criteria: Study inclusion

In this examination, studies comprised of those done during 2004 - 2025 and stated worth of artificial intelligence in cold chain. The selected studies focused on the various aspects and infrastructural components of cold chain, supplied an outline of current state of cold chain, barriers and factors leading to food loss and wastage, and discussed the strategies for waste minimization. Publications during the period 2004 to 2025 were considered for the study with book chapters, peer-reviewed journal articles and conference papers included. Publications that addressed non-food supply chains such as pharmaceuticals, chemicals, etc were not included. Also, only publications in English language were considered for the purpose of globalized understanding. Publications that were merely editorials or having one row representation were excluded from consideration.

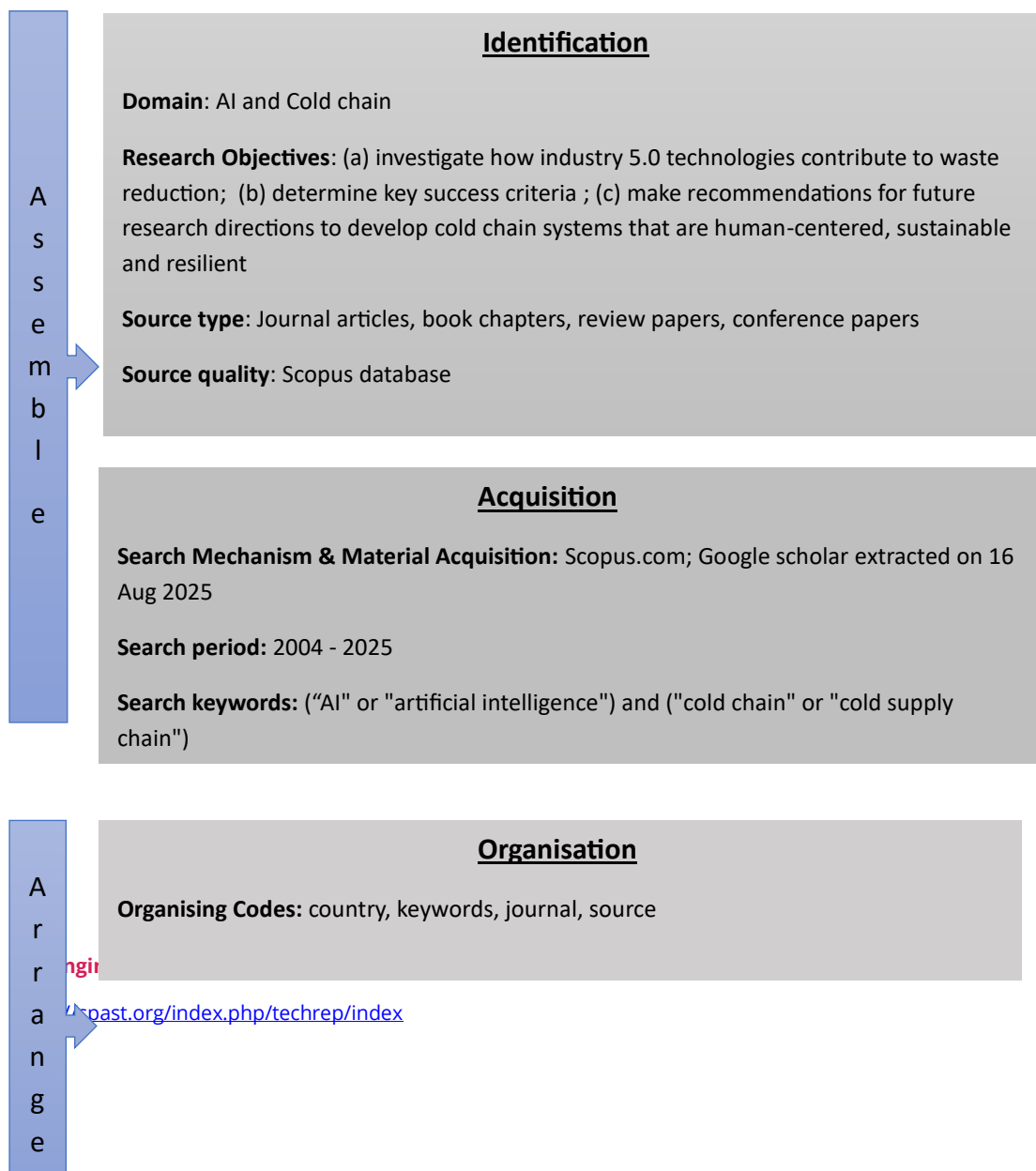
Screening and data abstraction process

Our screening procedure followed SPAR-4 tool, proposed by Paul [25] with title, abstract, and full-text screening stages. Studies that met the initial inclusion criteria based on title were retained. Concurring with the stages of the tool which are as given below: I] first stage encompasses identification of the area for conducting the examination; developing research questions post literature review; and specifying the types of articles to be extracted. This stage

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<https://spast.org/index.php/techrep/index>

also includes application of search criteria for extracting the required dataset. II] Here, the procedure for organisation of data analysis is designated. The stage also consists of elimination of those records which do not pertain to the domain under study referring to purification of dataset. III] The stage is marked with the agenda and analysis of data followed by reporting of the dataset through different types of exhibits. Any constraints are also indicated. Figure 1 depicts the different phases as per SPAR-4 model.



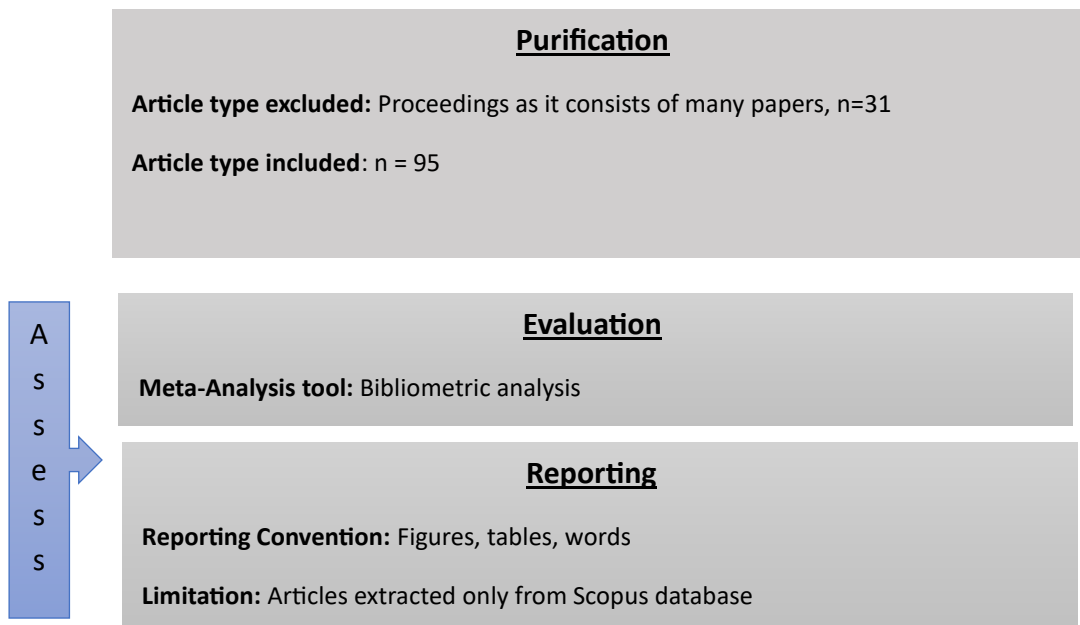


Figure 1. LR as per SPAR-4 tool

4. Analysis and Results

The visualization generated using VOSviewer software represents a bibliometric network map highlighting research themes and keyword co-occurrences. The central and most prominent cluster is “*artificial intelligence*,” closely linked with terms like *machine learning*, *decision making*, *supply chain management*, *forecasting*, and *optimization*, indicating their high research relevance and interconnections (Figure 2). Surrounding clusters reveal specialized applications such as *waste management*, *energy utilization*, *vehicle routing problems*, *food preservation*, and *blockchain traceability*, suggesting AI’s role in diverse domains ranging from logistics and sustainability to agriculture and resource efficiency. The dense clustering and interlinkages demonstrate that AI serves as a core enabler of decision support, optimization, and efficiency enhancement across multiple sectors, with supply chain management and sustainability-related topics including waste minimization and energy optimization that are emerging as significant research directions.

				performance dashboards
3 (Red)	Optimization and Control	Optimization algorithms; Controlled studies; Allocation methods; Computer control; Benchmarking; Regression models	Static optimization models that fail in dynamic environments Limited use of adaptive control systems in cold chain logistics	Develop real-time adaptive optimization algorithms Integrate digital twins for simulation-based control Benchmark hybrid models combining AI and traditional control systems
4 (Blue)	Food and Agriculture	Food preservation; Biology; Bioinformatics; Manufacturing; Bibliometrics	Insufficient focus on sustainable food preservation Limited application of bioinformatics in cold chain diagnostics Underutilization of bibliometric insights for strategic planning	Innovate preservation techniques using smart packaging and phase-change materials Apply bioinformatics for microbial risk prediction and shelf-life modeling Use bibliometric mapping to identify emerging research hotspots
5 (Yellow)	Emerging technologies	Blockchain; Traceability; Cloud computing; Aerial vehicles; Active/passive cooling systems; Phase change materials; Carbon constraints	Low adoption of emerging technologies in developing regions Unclear regulatory frameworks for drone and blockchain use Environmental trade-offs of cooling technologies	Promote pilot projects and public-private partnerships for tech adoption Develop harmonized regulatory frameworks for digital logistics Conduct life-cycle assessments to evaluate environmental impacts

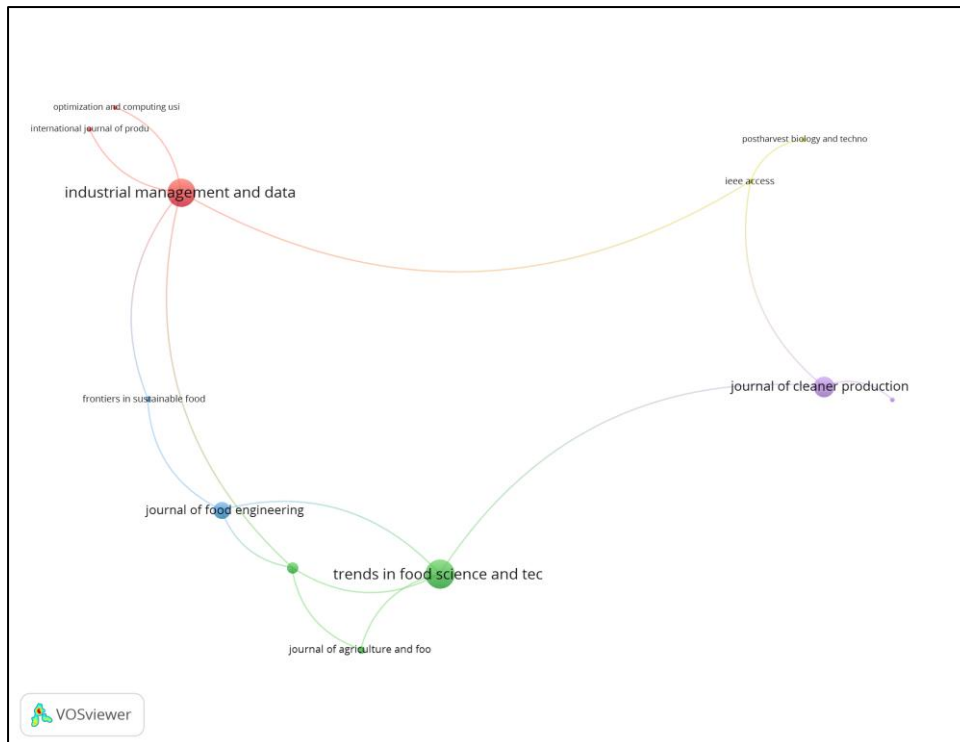


Figure 3. Journals and their citation contribution

The visualization depicted above (Figure 3) is a journal publication map showing how different academic journals are interconnected in research themes. At the center, *Trends in Food Science and Technology* appears as a major hub, strongly linked with journals such as *Journal of Food Engineering* and *Journal of Agriculture and Food*, indicating that it plays a central role in connecting food science, agriculture, and engineering research. Another important node is *Industrial Management and Data Systems*, which connects with journals like *International Journal of Production Research* and *Optimization and Computing*, suggesting a focus on data-driven optimization and management in industrial processes. On the sustainability side, *Journal of Cleaner Production* and *Frontiers in Sustainable Food Systems* are connected, showing emphasis on environmental aspects and sustainable practices. Additionally, *Postharvest Biology and Technology* and *IEEE Access* indicate a technological and postharvest preservation dimension within this research landscape.

Overall, the map highlights two major clusters: one revolving around food science, agriculture, and engineering, and the other around industrial management, optimization, and sustainability. The links among them suggest increasing interdisciplinary collaboration where data-driven industrial management and technological innovations are being applied to enhance sustainability and efficiency in food systems and production processes. Table 2 presents the contribution of journals towards publication and citation.

Table 2. Publications and Citations of top 5 journals

Journal	Publications	Citations
Industrial management and data systems	2	266
Trends in food science and technology	4	270
Journal of cleaner production	1	143
Journal of food engineering	2	91
Comprehensive reviews in food science and food safety	1	43

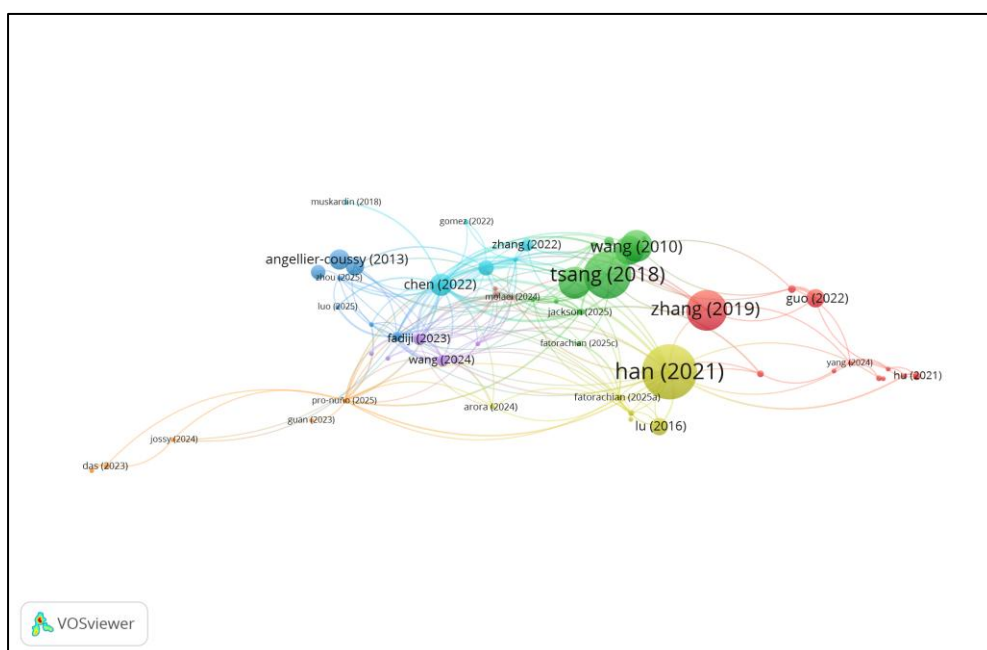


Figure 4. Bibliographic coupling vs documents

The visualization in figure 4 is a co-authorship or co-citation network map showing how different authors are connected through their research collaborations or shared citations. Larger nodes, such as Han (2021), Zhang (2019), Tsang (2018), and Angellier-Coussy (2013), represent influential authors or highly cited works in this field. The map is divided into several clusters of authors (distinguished by colors), each representing a research community or thematic focus. For example, the blue cluster (Angellier-Coussy, Chen, Fadji, Wang 2024) seems to represent recent works (2022–2025) connected around materials, food, or packaging research. The green cluster (Tsang, Wang 2010, Zhang 2022) highlights foundational studies that continue to influence newer research. The yellow cluster (Han 2021, Lu 2016, Fatorachian 2025) shows strong contemporary activity, bridging older foundational works with new emerging studies. Meanwhile, the red cluster (Zhang 2019, Guo 2022, Hu 2021) reflects is focused on optimization or technological applications. Overall, the map indicates that the field is well-connected yet diversified into distinct thematic groups, with some seminal works

(2010–2019) still serving as anchors for more recent studies (2021–2025). The strong interlinkages between clusters suggest active interdisciplinary collaboration, where newer researchers are building upon both established and emerging streams of knowledge.

Table 3. Top 5 documents

Title of the document	Authors	Name of Journal	Year	Citations
A comprehensive review of cold chain logistics for fresh agricultural products: Current status, challenges, and future trends	Jia-Wei Han, Min Zuo, Wen-Ying Zhu, Jin-Hua Zuo, En-Li Lü, Xinting Yang	Trends in Food Science & Technology	2021	261
An Internet of Things (IoT)-based risk monitoring system for managing cold supply chain risks Available to Purchase	Y.P. Tsang; K.L. Choy; C.H. Wu; G.T.S. Ho; Cathy H.Y. Lam; P.S. Koo	Industrial Management & Data Systems	2018	194
Low-carbon cold chain logistics using ribonucleic acid-ant colony optimization algorithm Author links open overlay panel	Li-Yi Zhang, Ming-Lang Tseng, Ching-Hsin Wang, Chao Xiao, Teng Fei	Journal of Cleaner Production	2019	143
A radio frequency identification and sensor-based system for the transportation of food Author links open overlay panel	Lixing Wang; S.K. Wok; W.H. Ip	Journal of Food Engineering	2010	90
Mitigating risks of perishable products in the cyber-physical systems based on the extended MRP model Author links open overlay panel	David Bogataj, Marija Bogataj, Domen Hudoklin	International Journal of Production Economics	2017	87

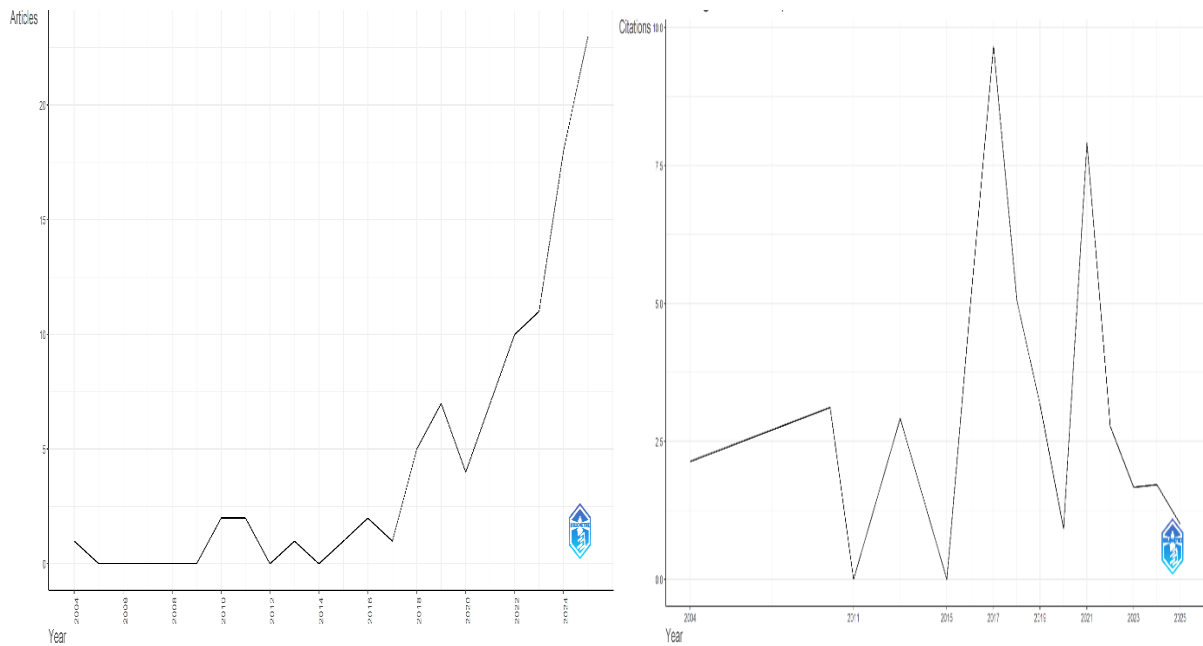


Figure 5. Year-wise number of publications & citations (Biblioshiny)

The figure 5, created using Biblioshiny, shows the trend in the number of research articles per year over the period from around 2004 to 2025 depicting publications and citations. In the early years (2004–2015), scientific production was relatively low and stagnant, with only 0–2 articles published annually, indicating limited research activity in this domain. From 2016 onwards, there is a noticeable upward trend, with a gradual increase in publications reflecting growing academic interest.

A more significant growth phase begins around 2018–2020, where the number of articles rises sharply, though with slight fluctuations. After 2020, the output accelerates considerably, crossing into double digits by 2022. The steep rise in 2023 and 2024, reaching over 20 articles in 2025, indicates an exponential growth in research, suggesting that the field recently gained strong momentum and is becoming an active area of scientific exploration. Overall, the trend shows a clear transition from a niche to a rapidly expanding research area, likely driven by technological advancements, policy relevance, or increased interdisciplinary interest. The rapid growth in the last 3–4 years suggests that this topic is currently emerging as a significant research frontier with increasing global attention.

The figure also depicts citations year-wise illustrating how the impact of publications has fluctuated between 2003 and 2025. In the early years 2003–2010, the average citation rate remained modest, around 2–3 citations per year, reflecting limited visibility of research in this period. A sharp decline is observed around 2011 and 2015, suggesting that publications from those years received comparatively little attention. However, the graph shows peaks in 2017 and 2021, where average citations reached their highest points, nearing 10 citations per year in 2017 and about 7–8 citations in 2021. These spikes suggest that seminal or influential papers were published in those years, significantly shaping the research landscape. After 2021, there is a notable decline, with average citations per year steadily decreasing through 2023–2025. This drop is expected because more recent publications have had less time to accumulate citations, making their immediate impact appear lower. Overall, the graph suggests that the field is still evolving, with a few

influential studies driving much of the citation activity, while newer research is still in the process of gaining recognition.

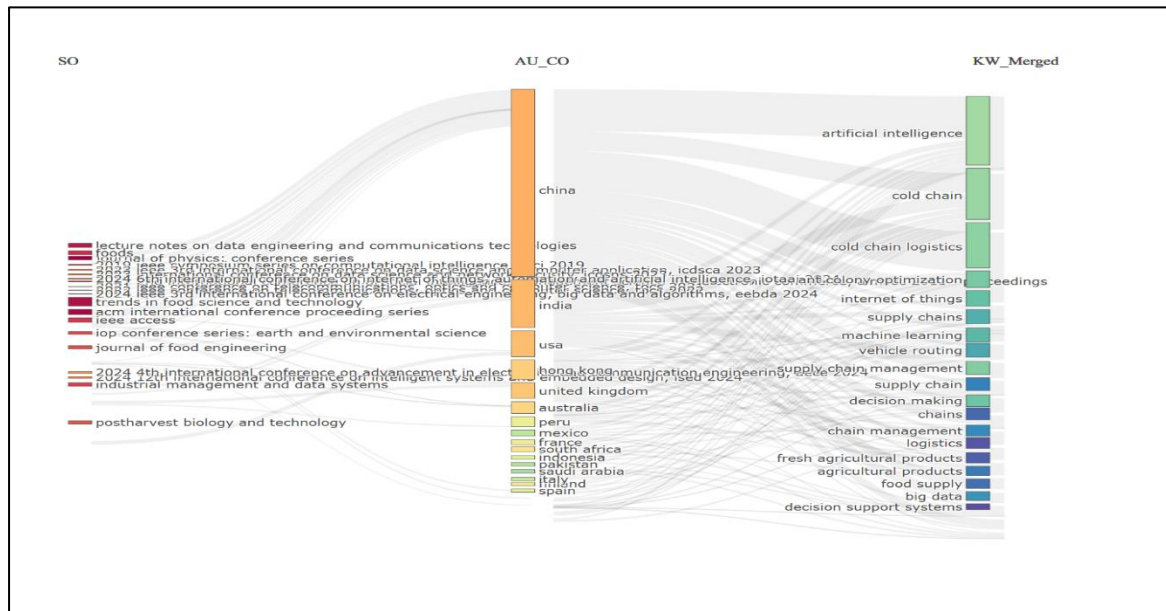


Figure 6. Three field plot: Sources vs Countries vs Keywords (Biblioshiny)

The visualization presented in figure 6 is a three-field plot (Sankey diagram) created in Biblioshiny, showing the relationships between sources of publication (SO), contributing countries (AU_CO), and research keywords (KW_Merged). On the left, the publication sources include journals and conference proceedings such as *Industrial Management and Data Systems*, *Journal of Food Engineering*, *Postharvest Biology and Technology*, and *IEEE Access*. These indicate that the research is published in a mix of engineering, management, food science, and technology-oriented outlets, reflecting the interdisciplinary nature of the field. In the middle, the countries most active in this research are prominently China, India, and the USA (figure 7), with additional contributions from countries like the UK, Australia, France, and Mexico. The thickest flows connect China and India, suggesting they are leading contributors in terms of publication volume. On the right, the keywords highlight dominant research themes such as *artificial intelligence*, *cold chain*, *cold chain logistics*, *supply chains*, *machine learning*, *Internet of Things (IoT)*, *decision making*, and *big data*. This suggests that much of the research is focused on integrating Industry 5.0 technologies (AI, IoT, big data, machine learning) into supply chain and logistics systems, particularly in areas like food supply, cold chain management, and agricultural products. Overall, the diagram shows that research on AI and digital technologies for supply chain and food logistics is largely driven by China, India, and the USA (figure 7), with a strong focus on waste minimization, efficiency, and sustainability in food systems through the application of Industry 5.0.

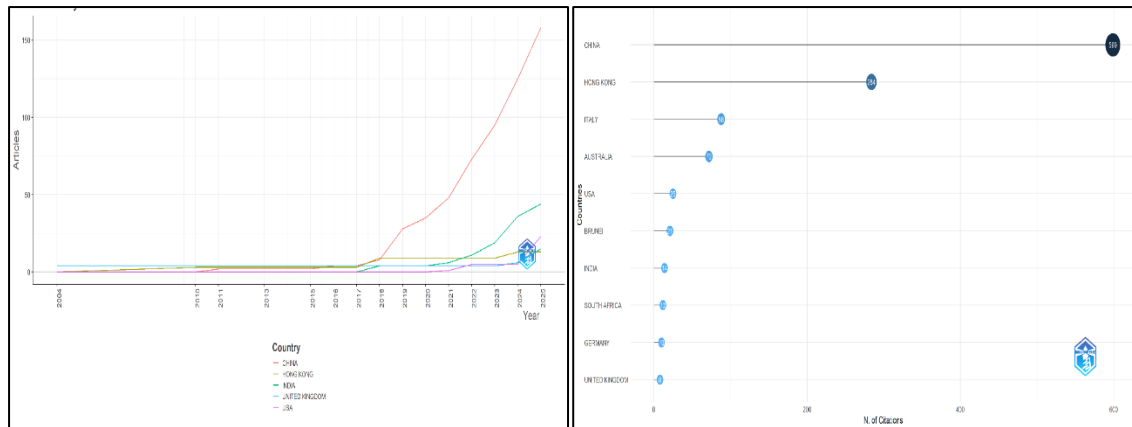


Figure 7. Countries production & citation over time



Figure 8. Treemap of keywords

Figure 8 depicts a treemap showing the relative frequency of keywords used in research field. Each block represents a keyword, and its size reflects the number of occurrences, while the percentage indicates its proportion within the dataset. The largest blocks are “sustainability” (100, 11%), “cold chain” (95, 10%), and “sustainable development” (76, 8%), showing that sustainability and cold chain management are the dominant themes in this research area. Closely following are “cold chain logistics” (38, 4%), “supply chains” (36, 4%), “supply chain management” (33, 4%), and “refrigeration” (28, 3%), which emphasize the role of logistics and supply chain processes, particularly in perishable goods, where efficiency directly affects waste minimization.

Other notable keywords include “environmental impact,” “energy efficiency,” “food waste,” “food storage,” “carbon,” “optimization,” and “decision making”. These indicate that researchers are actively addressing how Industry 5.0 tools (optimization models, AI-based decision support, energy-efficient systems) can reduce waste and carbon emissions while improving food supply chain resilience. Overall, the treemap reveals that research in this domain is strongly driven by sustainability goals, food and cold chain logistics, and supply chain management, with emerging attention to carbon footprint reduction, optimization techniques, and waste minimization strategies. This highlights how Industry 5.0 technologies are increasingly being integrated into food and logistics systems to achieve both environmental and operational efficiency.

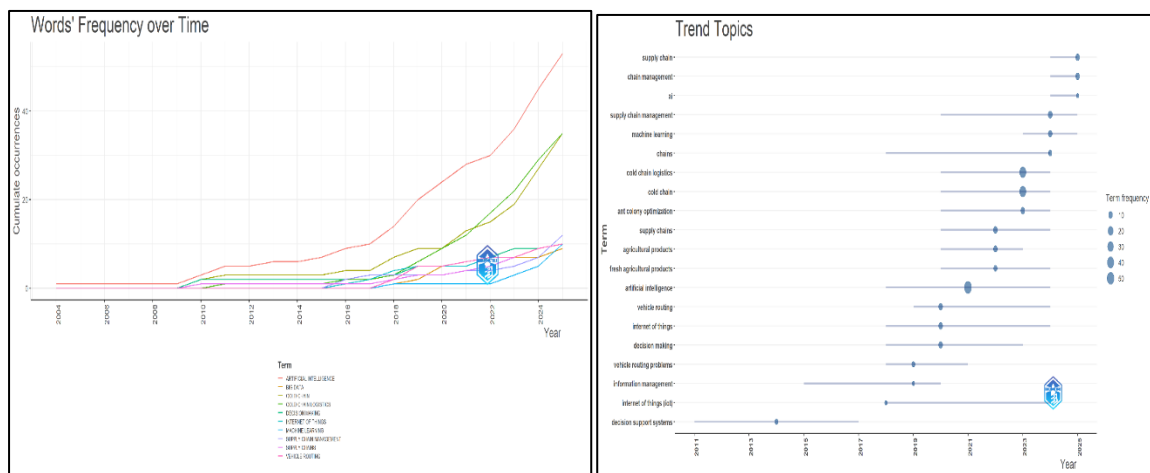


Figure 9. Words’ frequency over time vs Topic trends

Figure 9, “Words’ Frequency over Time”, shows the cumulative occurrences of key research terms from 2004 to 2025, highlighting how focus areas have evolved. The most prominent rise is seen in “artificial intelligence”, which has surged sharply since 2016, reflecting its central role in modern research. Closely following are “big data” and “cold chain”, both showing steady growth, especially after 2020, indicating increasing emphasis on data-driven decision-making and supply chain resilience. Terms like “machine learning,” “internet of things,” “supply chain management,” and “decision making” also exhibit noticeable upward trends, though at a slower pace, suggesting their supportive but significant role in the broader context. Overall, the graph highlights how Industry 5.0 technologies (AI, IoT, big data, ML) are increasingly integrated with supply chain and logistics (cold chain, vehicle routing) research, driving innovation in efficiency, waste minimization, and sustainability. The “Trend Topics” chart visualizes the emergence and growth of research themes over time, where the size of each bubble represents the frequency of term usage. Earlier years (2011–2016) show minimal activity with scattered mentions such as decision support systems and information management, but from around 2018 onward, research interest expands rapidly. By 2020–2023, terms like artificial intelligence, machine learning, cold chain logistics, cold chain, and supply chain management emerge strongly, marked by larger bubbles, indicating their growing dominance in the field. More recent years (2022–2025) highlight a surge in AI-driven optimization techniques, supply chain integration, IoT, and vehicle routing problems, reflecting the increasing reliance on digital and smart technologies for efficiency and

sustainability in supply chains. Overall, the chart demonstrates a clear shift from traditional cold supply chain/logistics focus toward technology-enabled, AI- and IoT-driven innovations, with 2020 onward marking the most significant acceleration in research interest.

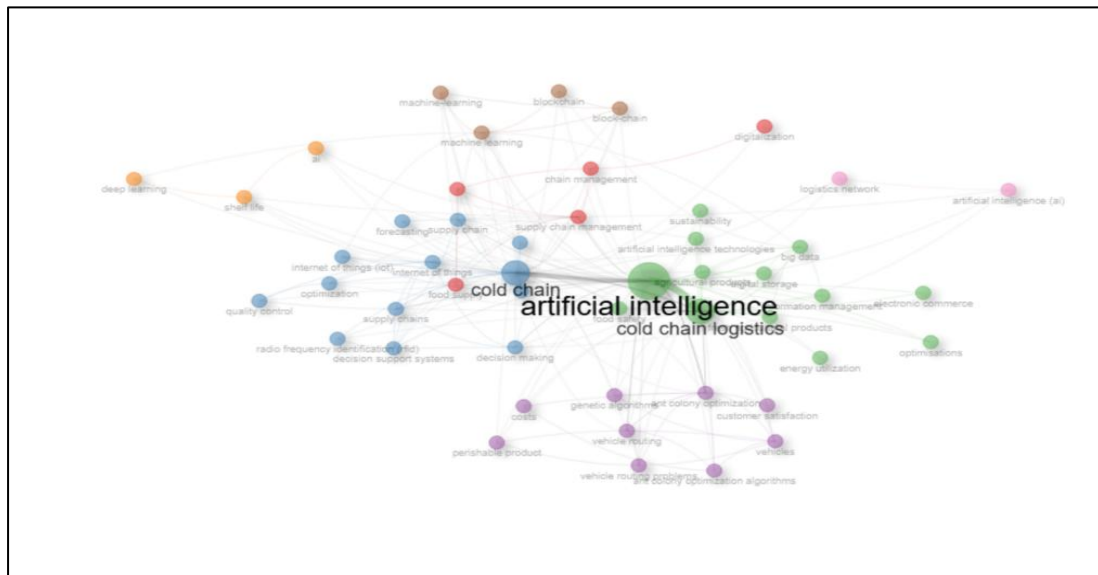


Figure 10. Co-occurrence network

Based on figure 10, it can be derived that *cold chain* is the central theme suggesting a strong focus on technological integration and operational efficiency. *Artificial Intelligence* having highest betweenness (599.56) indicates a pivotal role in linking diverse topics. *Cold chain logistics* also scores high thereby reinforcing the synergy between *AI* and *cold chain optimization*. Terms like *food safety*, *fresh agricultural products*, and *sustainability* though have low centrality however indicate emerging but underexplored areas. This suggests a growing interest in reducing spoilage and improving traceability in perishable goods.

5. Discussion

The co-word network analysis reveals a dynamic and evolving landscape in cold chain research, where *technological integration*, *logistics optimization*, and *artificial intelligence* emerge as central themes that underscore their pivotal role in shaping interdisciplinary strategies for reducing waste and enhancing efficiency.

A clear trend is the convergence of *AI-driven decision-making*, *IoT-enabled monitoring*, and *advanced routing algorithms*, which collectively offers transformative potential for minimizing spoilage, improving traceability, and optimizing resource utilization. While sustainability-related terms such as *food safety*, *energy utilization*, and *sustainability* currently exhibit lower centrality, their presence signals a growing research interest in environmentally responsible cold chain practices. To effectively reduce waste in cold chains, future strategies must prioritize upon: (i) predictive analytics and machine learning for demand forecasting and inventory control; (ii) IoT and RFID technologies for real-time visibility and state monitoring; (iii) optimization algorithms for efficient routing and collaborative planning; (iv) blockchain and digital platforms for transparency and collaborative planning. In sum, the integration of intelligent technologies with sustainable logistics practices represents a promising frontier for

cold chain innovation. By aligning operational efficiency with environmental stewardship, researchers and practitioners can drive meaningful progress toward resilient and waste-minimized supply chains. The first strategy will help forecast accurately, optimise resources, minimize delays and reduce spoilage. The second strategy will help integrate the sensors for real-time temperature and humidity monitoring. RFIDs will help in tracking product movement and shelf life enabling proactive interventions. The optimized logistics and routing strategy can employ vehicle routing problem solutions to reduce transit time for perishable goods and also consider multi-objective optimization to balance cost, time and environmental impact. Blockchain used will help secure transparent records of product handling and storage conditions while digital platforms can facilitate collaborative planning across the cold chain partners. Along with above strategies, decision support tools also can be employed to incorporate real-time data, historical trends and sustainability metrics to guide warehouse operations, transport scheduling and emergency responses.

The present analysis highlights the growing prominence of sustainability, cold chain logistics, and supply chain management in academic and industrial discourse, particularly under the umbrella of Industry 5.0. Over the years, research has shifted from traditional efficiency-oriented approaches toward more integrated frameworks that combine environmental, social, and technological dimensions. The increasing frequency of terms such as *artificial intelligence*, *machine learning*, *Internet of Things*, and *big data* indicates that technology-driven solutions are at the forefront of current supply chain innovation. The adoption of these tools is particularly evident after 2020, underscoring the heightened emphasis on digital transformation in response to global challenges such as the COVID-19 pandemic, climate change, and resource scarcity.

6. Conclusion

Bringing together the insights from the above analyses, it is evident that sustainability and efficiency remain the central themes in research on supply chains, cold chain logistics, and related areas. The treemap analysis highlights how concepts like sustainability, cold chain, and sustainable development dominate, supported by themes such as environmental impact, energy efficiency, food waste, and carbon emissions. This indicates a growing academic and industrial interest in aligning logistics and supply chain processes with global sustainability goals, particularly in the context of food, healthcare, and environmental preservation.

The trend over time shows a significant evolution in the vocabulary and focus of research. Between 2004 and 2010, progress was relatively slow, with minimal emphasis on digitalization or smart systems. However, from 2015 onward, there was a steep rise in the use of terms such as big data, artificial intelligence, IoT, and decision making, signalling the transition to Industry 5.0-driven practices. By 2020, these technologies gained momentum, reflecting real-world adoption of predictive analytics, machine learning, and smart systems to minimize waste, improve resource utilization, and streamline logistics.

The trend topics chart further reinforces this narrative, illustrating how recent years (2020–2023) have seen a surge in research linking AI, machine learning, IoT, vehicle routing, and optimization with supply chain management and cold chain logistics. The increasing size of bubbles in recent years shows not just the popularity of these themes but also their convergence. This reflects a paradigm shift where technological tools are no longer supporting functions but have become core enablers of sustainable, resilient, and efficient supply chains.

In conclusion, the overall trajectory suggests that the integration of Industry 5.0 technologies is central to minimizing waste and enhancing sustainability in logistics and cold supply chain systems. Industry 5.0 will remain pivotal in advancing waste minimization, enhancing decision-making, and building resilient cold chains. The emphasis has shifted from addressing individual inefficiencies (such as food waste or energy utilization) to adopting holistic, technology-driven solutions that optimize decision-making, reduce carbon footprints, and strengthen resilience. Going forward, the convergence of sustainability goals with digital innovation will likely define the next phase of research and practice, creating smarter, greener, and more adaptive cold chain ecosystems.

6.1 Theoretical & Practical Implications

This study contributes to the body of knowledge on sustainable cold chains by bridging classical theories of logistics and operations management with emerging perspectives on digital transformation. The findings reinforce the link between technological adoption and ecological outcomes, particularly in the context of food and pharmaceutical cold chains where waste minimization is critical. The results also demonstrate how advanced analytics and intelligent systems reshape traditional approaches to supply chain optimization.

For practitioners, the results highlight the urgent need to embed digital technologies into logistics and supply chain operations. Managers can leverage artificial intelligence and predictive analytics to improve demand forecasting, minimize spoilage in cold chains, and optimize vehicle routing for reduced carbon emissions. IoT-enabled sensors offer real-time monitoring of product conditions, thereby enhancing traceability and reducing inefficiencies. Policymakers can also draw from these insights to design incentives and regulatory frameworks that encourage green logistics and the adoption of smart technologies. Importantly, the findings demonstrate the potential for low-cost digital solutions in emerging economies, where improving cold chain infrastructure directly impacts food security, waste reduction, and sustainable development.

Although significant progress has been made, several avenues remain open for future inquiry. First, the integration of emerging technologies such as blockchain, digital twins, and edge computing warrants further exploration, particularly in enhancing transparency and resilience. Second, the development of standardized sustainability metrics for digitalized supply chains would enable more consistent measurement of environmental and social outcomes. Third, there is a need to investigate the role of Industry 5.0 tools in risk management and resilience-building, especially under global disruptions such as pandemics or geopolitical conflicts. Sector-specific studies, particularly in agriculture, pharmaceuticals, and healthcare, could yield valuable insights into how cold chain optimization reduces waste and improves access. Finally, future research should consider human-centric approaches, examining how workforce skills, organizational culture, and decision-making processes interact with advanced technologies to shape sustainable CC practices. Sustainability and energy utilization are currently low in centrality but crucial for long-term impact. There's need to further explore AI-driven sustainability models, especially for energy-efficient cold storage and carbon footprint reduction. To conclude, convergence of sustainability and Industry 5.0 represents a transformative pathway for minimizing waste and fostering resilient cold chains.

By integrating theoretical, practical, and forward-looking perspectives, this study underscores the importance of continued research and innovation in advancing sustainable logistics in the digital era.

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