Sustainable Cold Chain and Information Technology

Madhu Arora[1], Pragya Prashant Gupta[2]

[1]Post-doctoral researcher and research associate, Lincoln Global Post Doctoral and Researcher Programme (LGPR) Lincoln University, Malaysia, pdf.madhuarora@lincoln.edu.my, shamayutu@gmail.com

[2]Professor and Dean, Faculty of Commerce and Management Studies, Future University, Bareilly, dr.pragyaprashant@gmail.com

---

Abstract: With changing consumer preferences, social structures, increase in food wastage and losses, and rising health and wellness awareness, sustainability in cold chain has become a pre-dominant concern. Technology can play a significant role in curbing such issues while enhancing sustainability. Considering the above, the study focusses on the role of emerging technologies in making a cold chain sustainable. Technologies including IOT (internet-of-things), AI (artificial intelligence) and Blockchain have been considered in the study to highlight the benefits and impact of use of technology on the cold chain. As per the study, there are numerous benefits with some of them being: reduced wastage, enhanced efficiency, improved trust, to name a few. The findings of the study will help set scope for future research for examining the factors influencing towards a sustainable cold chain. A mixed approach of qualitative and quantitative analysis is proposed in the study to analyse the different sustainability indicators for a cold chain for future research scope. It will also assist the policy makers and decision makers to prioritize their efforts towards a sustainable cold chain.

Keywords: Cold chain, Technology, IT, Sustainability, Food wastage, Food losses.

Introduction

The cold chain in the recent times has emerged as critical enabler of sustainable economies by ensuring effective storage, processing and transport of goods perishable in nature, whether the products are pharmaceuticals, food, beverage or other miscellaneous categories. However, the cold chain network which is specifically designed to maintain the safety and quality of the perishables has become the concern for raising carbon footprint. This is owing to the energy-intensive requirements in the form of infrastructural equipment such as cold storages, reefers, pre-coolers, etc. It therefore becomes an imperative need to reach a balance between cold chain effectiveness and sustainability. The central theme of the study is to understand how the cold chain effectiveness, with special reference to food products, be enhanced while meeting the UNSDGs (United Nations Sustainability Goals). This study thus attempts to frame the discourse on sustainable cold chain as not merely a technological upgrade but a systemic transformation necessary for a resilient, responsible cold network for the future times as well.

Related work

The safety and attributes of food products largely is dependent upon the supply chain through which it moves (Jaelani, 2025). Appropriate environmental conditions, such as temperature, humidity,

moisture need to be maintained during storage and transportation (Bradford, 2020). Inclusion of emerging technologies can significantly bring about a transition in sustainability concerns related to food cold chain (Arora & Gupta, 2025). Especially so considering the growing demand for different varieties of food products, time constraints, resource scarcity and global warming concerns, there is tremendous pressure upon the food cold chain to cut upon waste and losses and develop towards sustainability. Roughly around 15-20% of global food losses owe it to ineffective food cold chain further augmenting the triple bottom line sustainability concerns (Tariq & Ali, 2025).

Technology like data analytics, artificial intelligence, blockchain can contribute in making robust, resilient and sustainable cold chain systems. Such technologies can contribute dominantly towards reduction of wastage and losses. Whether it is monitoring and control of environmental conditions, demand forecasting, machine and equipment maintenance, usage and consumption of raw material and production, resource optimization, technology can help in improving efficiency, effectiveness and circularity in all such processes. Different stakeholders of a cold network will also reap the benefits in the form of reduced costs, compliance with UNSDGs and have a competitive edge (Kumar, Tyagi & Sachdeva, 2023). Table 1 depicts the three themes, namely, cold chain, sustainability and emerging technologies, identified with significant work in the related themes.

Table 1. Themes for the Literature review and significant work in the related theme

Theme	***Author***	***Inference***	***Gaps***
Cold chain	Mustafa (2024); Qian (2022); Shashi, Centobelli, Cerchione & Ertz (2021); Bhatnagar(2019); Bremer(2018); Ali(2018); Singh & Shabani (2016)	• A firm's performance in CC is significantly impacted by temperature breakdowns, poor packaging, and quality degradation • Using appropriate technology and monitoring shelf life can help reduce waste • Businesses can generate competitive advantage by using innovative methods to produce what is most pertinent to their operational plan	1.Need to study effect of temperature breakdowns, quality deterioration, waste reduction and other issues on performance of SCC 2. Need for designing innovative SCC with the application of emerging technologies and integrating all information flows to achieve competitive advantage
Sustainability	Zhang (2024); Turan (2022); Chen (2022); Ertz (2022); Shi (2022);	• Using technology and controlling the temperature properly will help to preserve quality during distribution. • Research on sustainability is still in nascent stage. • The performance of agricultural supply chains as a whole may be significantly impacted by green agro-sector activities.	1. It is necessary to research the role that emerging technology can play in ensuring the quality of food while they are being transported. 2. More emphasis must be given to sustainability. 3. Sustainability must be properly taken into account for waste minimization.

Emerging Technologies	Grover (2024); Veena (2024); Gonzalez et al (2021); Batwa & Norman (2020); Badia-Melis (2018);	• By collecting, transferring, and sharing the real data of agri-food in production, processing, warehousing, distribution, and sales, IT may achieve traceability with reliable information throughout the whole agri-food SC, which would effectively guarantee food safety, quality and SC performance. • WSN can efficiently lower waste in the cold chain and enhance process quality. • Information and knowledge needs to be available to all the SC partners for enhanced performance which can lead to enhanced competitive advantage	1.For greater traceability, food safety and quality, and better integration of the various CSC linkages, the role of IT and cutting-edge technologies in the FF industry needs to be investigated. 2.Role of IT in reaching sustainability and competitive advantage needs to be examined.

As per the study by Arora (2025), digital technologies can be effectively employed in the cold chain systems for improvement in temperature control, minimization of food waste and improvement in energy utilisation. Employment of blockchain can improve substantially on the traceability aspect as well as enhance transparency in cold chain operations resulting not only in food safety but will also help increase consumer trust in the food products. Internet-of-Things can truly make real-time tracking of various environmental conditions such as humidity, temperature and other storage conditions. It can also contribute in planning and optimization of routes for deliveries of temperature-sensitive products. Use of artificial intelligence for the purpose of prediction can not only help predict needs for demand and storage but also optimize storage requirements, manage cold chain disruptions as well as reduce further spoilage.

Key Contribution

The paper contributes by emphasizing upon the need for a sustainable cold chain made possible by incorporation of technology in various components of a cold chain system.

Results and Discussion

This paper is a pre-requisite to the study that will incorporate a mixed-method approach employing both quantitative and qualitative analysis. Fig 1 exhibits the process flow diagram of the cold chain with sustainability interventions at various points. The process flow is aligned with the UNSDG 12 (Responsible Consumption & Production) and 17 (Partnership for the Goals) (Giri, 2025). Some of the challenges related to sustainability in cold chain include: energy consumption, food wastage, carbon emission, lack of transparency, and regulatory compliance (Zhou, 2025; Bentyn & Konecka, 2024; Wognum, 2011).

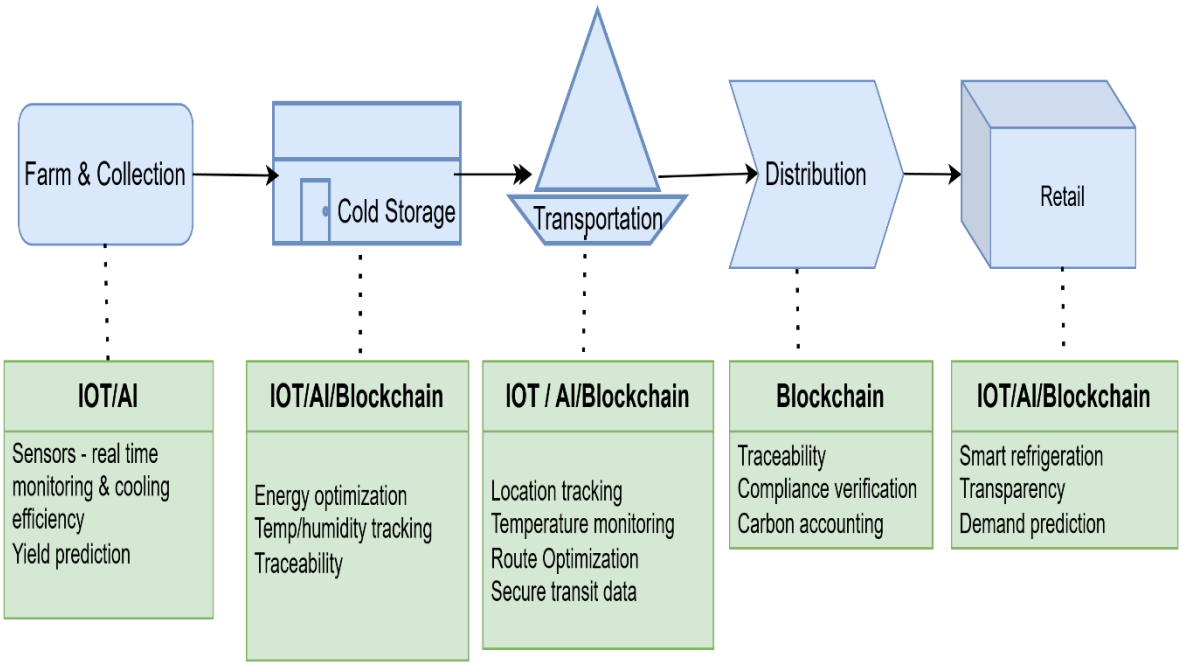

Fig 1. Process Flow Diagram with Sustainability Interventions

At the farm and cold storage stages, IOT and AI enable real-time monitoring coupled with predictive decision-making. Sensors that can be deployed in the farm will help capture data such as condition of the soil, crop health, temperature, etc. AI model can then utilise this data for further prediction of the yield and detection of risks pro-actively. In the cold storages, IOT devices can track temperature and humidity with AI optimizing upon energy consumption. With these practices, spoilage will reduce, control will improve while perishable goods will remain safe for consumption.

During transportation and storage, an integration of IOT, AI and Blockchain technologies can strengthen operational efficiency and trust. IOT devices deliver continuous tracking and monitoring of temperature (Fatorachian, 2025) and location while AI offers support in optimization of route and thereby logistics planning thereby reducing energy consumption (Nozari, 2025). Blockchain ensure tamper-proof documentation whether it is related to storage conditions or movement log (Zhang, 2022. Jo, 2022).

At the distribution and retail stages, blockchain ensures end-to-end traceability, compliance verification and ethical carbon accounting. Both stakeholders and consumers can validate the product origin, handling conditions, etc. In retail, IOT-enabled smart refrigeration systems maintain optimum storage conditions while AI offers support in demand prediction and inventory planning cutting down on waste therefore. Synergistically, these technologies help create a transparent, efficient and responsive supply chain that improves safety, sustainability and consumer trust. Fig 2. Depicts the various challenges as addressed by the emerging technologies.

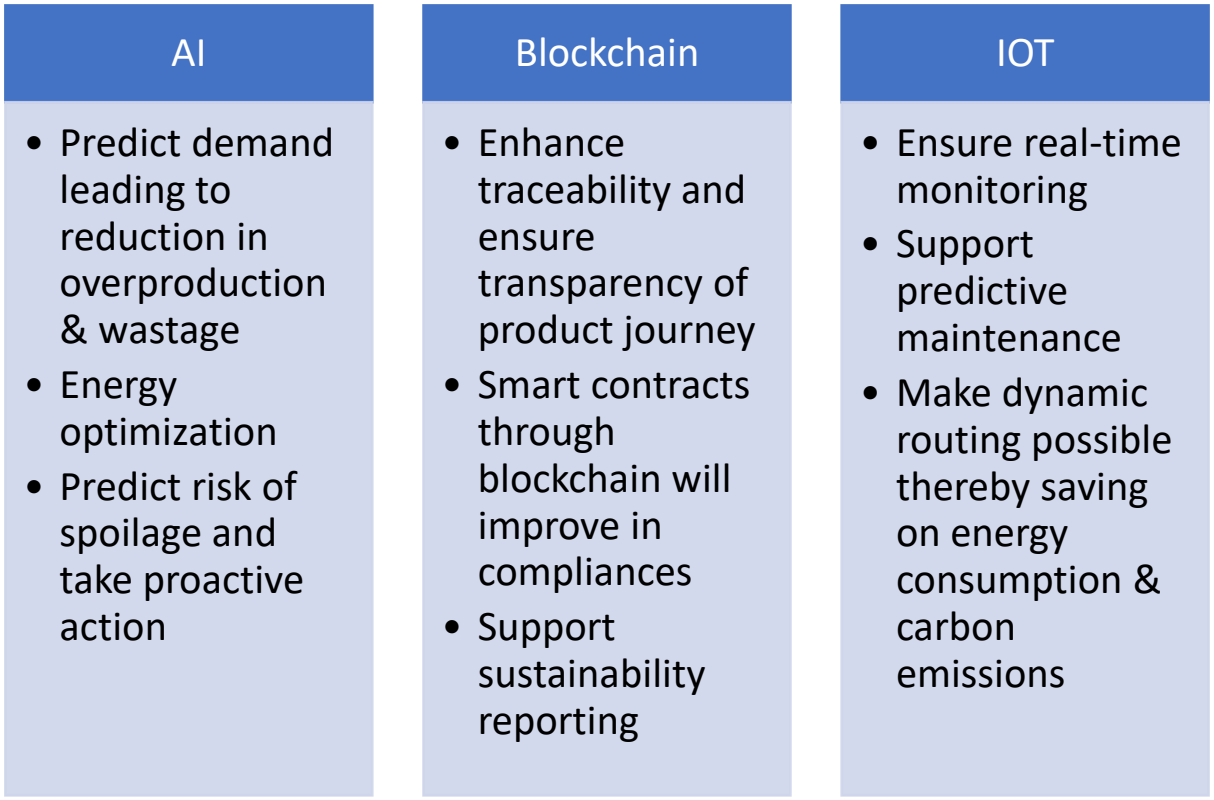

Fig 2. Sustainability challenges addressed by emerging technologies

The integration of AI, IOT and blockchain can directly impact the stakeholders of the cold chain system. The stakeholders being considered for the purpose of this study are the retailers, logistics and the cold storage service providers. Each of the technologies can help offer value, enhanced efficiency, sustainability and trust. For the cold storage service providers, use of IOT, AI and Blockchain will benefit in the following ways:

- Energy efficiency will improve and spoilage will reduce through real-time monitoring of refrigeration conditions
- Equipment reliability will improve and downtime and risks will reduce through predictive maintenance
- Regulatory adherence and accountability will strengthen owing to transparent compliance in the records

It can therefore be indicated that the use of information technology will impact the cold storage facilities in the form of cost savings, reduced waste and robust compliance positioning lending them enhanced reliability. For the logistics including the logistics service providers, use of technologies will have benefits as mentioned below:

- Tracking of the shipment and monitoring of the status will help reduce losses while in transit
- Route optimization will result in lowering of emissions and fuel consumption
- Predictive planning will ensure in-time deliveries
- Visibility related to shipment status and timelines will help build trust not only with consumers but also regulators

The employment of technologies will result in improved credibility along with increased efficiency and sustainability. Retailers too as a significant stakeholder of the cold chain will largely benefit as follows:

- Risk of holding spoiled goods in inventory is reduced owing to real-time product status data being easily accessible
- Overstocking or shortages can be avoided by improving inventory management
- Consumer trust and brand reputation will be enhanced through improved traceability and carbon accounting

The retailers thus benefit from the optimized inventory, consumer confidence, and compliance assurance thereby strengthening competitive edge. Together the stakeholders experience mutually reinforcing benefits resulting in a smarter, more transparent and sustainable cold chain. Fig 3 exhibits the above benefits in pictorial representation.

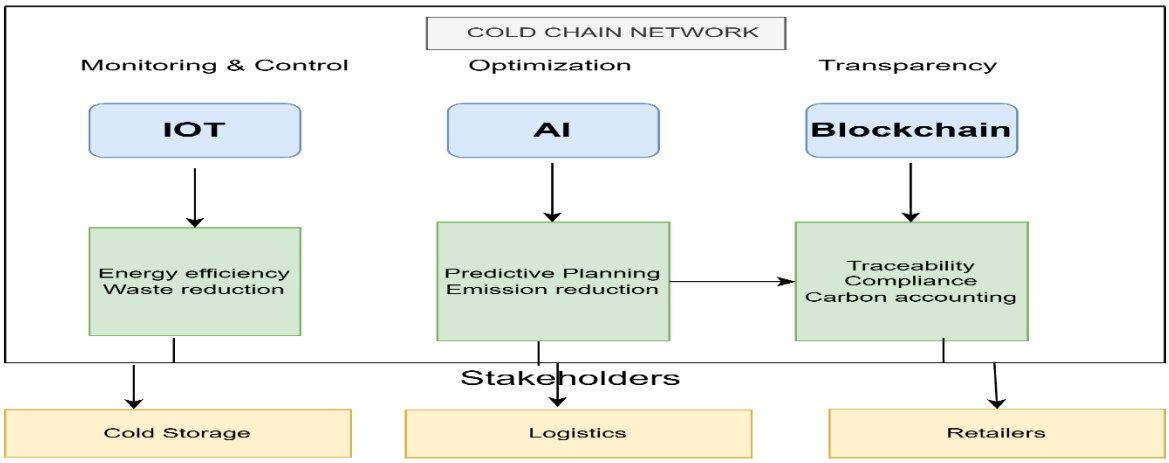

Fig 3. Stakeholder Impact analysis

Conclusions

Considering the above study, following conclusion can be built upon:

The cold chain sector is facing numerous rising challenges owing to changing social structures, consumer preferences, increasing awareness and health concerns and increasing wastage and losses. All such challenges make sustainability a dominant factor to adopt in cold chain operations.

1. Even though, cold chains are designed to ensure safety and quality of food, current practices lead to inefficiency, environmental issues and gaps in compliances. Emerging technologies can significantly address such challenges.
2. This study has only presented the need of emerging technologies, need of identification of sustainability indicators and the prioritization of the sustainability indicators.
3. Internet-of-Things enables real-time monitoring of temperature, humidity, and energy use and can significantly contribute towards reduction of wastage coupled with improved energy consumption. Artificial intelligence makes predictive planning possible which can result in optimized routes, demand forecasting, predictive maintenance resulting in enhanced operational reliability coupled with reduced emissions. Blockchain ensures transparency, strengthens compliances and supports sustainability reporting. Collectively, they result in waste reduction, increased efficiency, improved trust finally making the cold chain resilient, robust and sustainable for the future times.
4. The study only indicates the role of emerging technologies but does not throw any light on what are the sustainability indicators and what is their order of importance. Also, no empirical

analysis has been carried out in the present study. Future research can further identify the sustainability indicators as well as prioritize them to enable decision-makers and policy makers to further act upon investment related decisions.

References

1. Ali, I., Nagalingam, S., & Gurd, B. (2018). A resilience model for cold chain logistics of perishable products. *The International Journal of Logistics Management*, *29*(3), 922-941.
2. Arora, M., & Gupta, P. P. (2025). Waste minimization in food cold chain using Industry 5.0: Review Focus on Artificial Intelligence. *SGS-Engineering & Sciences*, *1*(3), https://spast.org/index.php/techrep/index
3. Badia-Melis, R., Mc Carthy, U., Ruiz-Garcia, L., Garcia-Hierro, J., & Villalba, J. R. (2018). New trends in cold chain monitoring applications-A review. *Food control*, *86*, 170-182.
4. Batwa, A., & Norrman, A. (2021). Blockchain technology and trust in supply chain management: A literature review and research agenda. *Operations and Supply Chain Management: An International Journal*, *14*(2), 203-220.
5. Bhatnagar, A., Vrat, P., & Shankar, R. (2019). Multi-criteria clustering analytics for agro-based perishables in cold-chain. *Journal of Advances in Management Research*, *16*(4), 563-593.
6. Bentyn, Z., & Konecka, S. (2024). Cold chain as a resilience feature of the supply chain in changing conditions of the environment. *Journal of Civil Engineering and Transport*, *6*(4), 17-25.
7. Bradford, K. J., Dahal, P., Van Asbrouck, J., Kunusoth, K., Bello, P., Thompson, J., & Wu, F. (2020). The dry chain: Reducing postharvest losses and improving food safety in humid climates. In Food industry wastes (pp. 375-389). Academic Press.
8. Bremer, P. (2018). Towards a reference model for the cold chain. *The International Journal of Logistics Management*, *29*(3), 822-838.
9. Chen, Q., Qian, J., Yang, H., & Wu, W. (2022). Sustainable food cold chain logistics: From microenvironmental monitoring to global impact. *Comprehensive reviews in food science and food safety*, *21*(5), 4189-4209.
10. Ertz, M., Centobelli, P., & Cerchione, R. (2022). Shaping the future of cold chain 4.0 through the lenses of digital transition and sustainability. *IEEE Transactions on Engineering Management*, *71*, 2812-2828.
11. Fatorachian, H. (2025). Integrating IoT and Blockchain for Sustainable Waste Management in Cold Chain Food Supply Chains: Enhancing Efficiency and Accountability. *International Journal of Automation, Artificial Intelligence and Machine Learning*, *5*(1), 7-25.
12. Giri, V., Madaan, J., Chan, F. T., & Varma, N. (2025). A methodological framework to analyze the impact of blockchain affordances on sustainable–resilient pharmaceutical supply chain performance. *Journal of Enterprise Information Management*, 1-33.
13. Villa-Gonzalez, F., Bhattacharyya, R., Athauda, T., Sarma, S. E., & Karmakar, N. C. (2022). Detecting breaks in cold chain integrity using chipless RFID time–temperature sensors. *IEEE Sensors Journal*, *22*(18), 17808-17818.
14. Grover, N. (2025). AI-enabled supply chain optimization. *International Journal of Advanced Research in Science, Communication and Technology*, 28-44.
15. Jaelani, I., Harsanto, B., Azis, Y., Sari, D., & Kaltum, U. (2025). Cold chain logistics challenges on sustainability: A systematic review. Sustainable Futures, 10, 101559.

16. Jo, J., Yi, S., & Lee, E. K. (2022). Including the reefer chain into genuine beef cold chain architecture based on blockchain technology. *Journal of Cleaner Production*, *363*, 132646.
17. Kumar, N., Tyagi, M., & Sachdeva, A. (2023). A sustainable framework development and assessment for enhancing the environmental performance of cold supply chain. *Management of Environmental Quality: An International Journal*, *34*(4), 1077-1110.
18. Mustafa, M. F. M. S., Navaranjan, N., & Demirovic, A. (2024). Food cold chain logistics and management: A review of current development and emerging trends. *Journal of Agriculture and Food Research*, *18*, 101343.
19. Nozari, H., Rahmaty, M., Foukolaei, P. Z., Movahed, H., & Bayanati, M. (2025). Optimizing cold chain logistics with artificial intelligence of things (AIoT): A model for reducing operational and transportation costs. *Future Transportation*, *5*(1), 1.
20. Qian, J., Yu, Q., Jiang, L., Yang, H., & Wu, W. (2022). Food cold chain management improvement: A conjoint analysis on COVID-19 and food cold chain systems. Food control, 137, 108940.
21. Shashi, Centobelli, P., Cerchione, R., & Ertz, M. (2021). Food cold chain management: what we know and what we deserve. *Supply Chain Management: An International Journal*, *26*(1), 102-135.
22. Shi, H., Zhang, Q., & Qin, J. (2024). Cold chain logistics and joint distribution: A review of fresh logistics modes. *Systems*, *12*(7), 264.
23. Singh, R., & Shabani, A. (2016). The identification of key success factors in sustainable cold chain management: Insights from the Indian food industry. *Journal of Operations and Supply Chain Management (JOSCM)*, *9*(2), 1-16.
24. Tariq, H., & Ali, M. H. (2025). Reducing food loss and waste within cold food supply chains–empirical evidence from developing economies. British Food Journal, 1-20.
25. Turan, C., & Ozturkoglu, Y. (2022). A conceptual framework model for an effective cold food chain management in sustainability environment. *Journal of Modelling in Management*, *17*(4), 1262-1279.
26. Veena, M., Sravani, K., Dhanapal, K., Kumar, G. P., Manaswini, C., & Basha, D. C. (2025). Blockchain Technology for Enhancing Traceability and Sustainability in Fish and Fishery Products: Comprehensive Review. *International Journal of Bio-Resource & Stress Management*, *16*(9).
27. Wognum, P. N., Bremmers, H., Trienekens, J. H., Van Der Vorst, J. G., & Bloemhof, J. M. (2011). Systems for sustainability and transparency of food supply chains–Current status and challenges. *Advanced engineering informatics*, *25*(1), 65-76.
28. Zhang, B., & Mohammad, J. (2024). Sustainability of perishable food cold chain logistics: a systematic literature review. *Sage Open*, *14*(3), 21582440241280455.
29. Zhang, X., Sun, Y., & Sun, Y. (2022). Research on cold chain logistics traceability system of fresh agricultural products based on blockchain. *Computational intelligence and neuroscience*, *2022*(1), 1957957.
30. Zhou, Q., Li, Y., Peng, Z., & Hu, J. (2025). Policy-anchored sustainability: Decarbonizing the food cold chain. *Renewable and Sustainable Energy Reviews*, *223*, 116077.