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Exploring Eco-Innovation Barriers to the Sustainability Transition in Cold Chain E-Fulfilment Systems

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ABSTRACT

The growing demand for cold chain e-fulfilment services has created challenges for implementing low-carbon practices due to the use of extensive energy and insulation materials required to maintain the desired service quality throughout the supply chain. This study applies the Fuzzy Best Worst Method with group decision-making capabilities to identify and prioritise eco-innovation barriers in the context of cold chain e-fulfilment. Through analysing expert opinions, it is found that (i) integration with legacy systems, (ii) high implementation costs, (iii) limited stakeholder engagement and communication, and (iv) limited awareness and education on eco-innovation are the most pressing eco-innovation barriers. Subsequently, insights and guidelines to integrate eco-innovation initiatives in cold chain e-commerce are suggested, highlighting the role of social eco-innovation. All in all, this research contributes to the next-generation sustainable development of cold chain e-fulfilment, aiming to balance environmental, social, and economic sustainability.

KEYWORDS

Sustainability, Eco-Innovation Barrier, Cold Chain E-Fulfilment, Group Decision Making, Fuzzy Best Worst Method

The significance of cold chain e-fulfilment has grown considerably in response to the expanding online shopping landscape and the escalating demand for fresh and frozen products directly delivered to consumers (Gu et al., 2021). Cold chain e-fulfilment refers to the end-to-end process of storing, handling, and delivering temperature-sensitive products ordered by customers through e-commerce platforms. It involves utilising specialised cold chain technologies, such as cold storage facilities, refrigerated vehicles, and thermal packaging, to maintain product quality, safety, and integrity from the point of origin to the final delivery to end customers (Tsang et al., 2020). The operational flow of cold chain e-fulfilment is more complex than traditional e-fulfilment processes, as it includes temperature-controlled warehousing, inventory management, order processing, picking and packing, transportation, and time-sensitive last-mile delivery (Lam & Tang, 2023; Salin & Nayga, 2003; X. Wang & Cao, 2021). As depicted in Figure 1, the cold chain e-fulfilment process generally begins with

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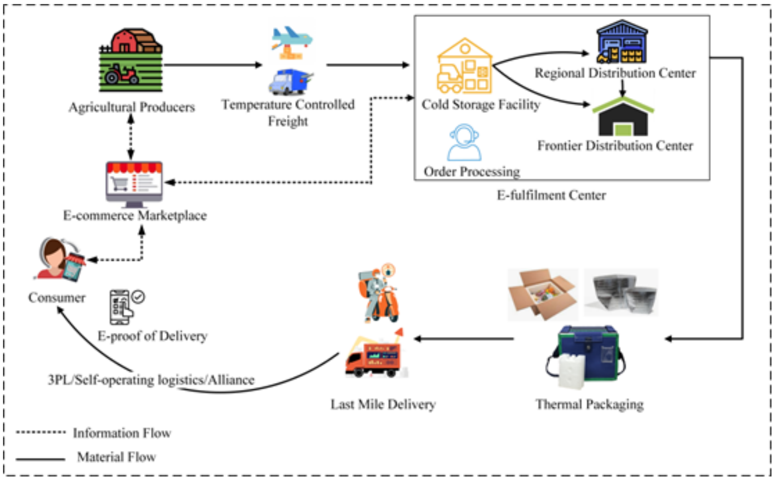
Figure 1. Overview of the generic process of cold chain e-fulfilment



procuring temperature-sensitive products from suppliers, which are then stored in specialised cold storage facilities. The process is initiated when a customer places an order through an e-commerce platform. The products are carefully selected, packaged using thermal materials, and loaded onto refrigerated vehicles. Real-time monitoring ensures that the temperature is strictly maintained during transportation. Finally, the products are delivered to the customers' doorsteps or designated delivery points. Cold chain e-fulfilment is crucial for meeting the increasing demand for fresh and frozen products directly delivered to customers through e-commerce platforms.

However, the rapid expansion of cold chain e-fulfilment services has raised concerns regarding its sustainability. This arises from the energy-intensive nature of cold storage facilities, thermal packaging materials, and refrigerated transportation, which can contribute to substantial greenhouse gas (GHG) emissions. Additionally, the heightened demand for swift and efficient product delivery within the context of e-commerce cold chains further exacerbates vehicle emissions. In the face of climate change impacts driven by carbon dioxide emissions, the adoption of sustainable practices that foster carbon neutrality within the logistics and supply chain industries becomes imperative (B. Wang et al., 2022; Wallach, 2023). As revealed by the findings of energy efficiency in the food cold chain, a significant proportion, approximately 40%, of the global food supply necessitates refrigeration at various stages of production and distribution (Gurrala & Hariga, 2022). Furthermore, the energy consumption associated with refrigeration accounts for a substantial portion, approximately 15%, of global energy usage (Gurrala & Hariga, 2022). Consequently, implementing eco-innovation practices within cold chain e-fulfilment is critical, as it is a viable solution to mitigate environmental strain and advance sustainability goals (Adekomaya et al., 2016).

Eco-innovation refers to creating and utilising innovative solutions that benefit the environment while being economically viable (Kemp & Pearson, 2008). Frondel et al. (2008) suggest that eco-innovation has the potential to generate mutually beneficial outcomes in terms of economic and environmental benefits. Similarly, Burki et al. (2019) propose that when logistics or supply chains adopt eco-innovation practices, they can increase business productivity, opportunities to enter new markets, and environmental sustainability. Therefore, integrating eco-innovation practices into the cold chain e-fulfilment process is valuable and can create a "win-win" situation.

However, the process of operationalising eco-innovation concepts in the cold chain e-fulfilment domain can face various barriers that must be addressed to balance economic growth and environmental sustainability (Ong & Lee, 2020). These barriers can arise from technological limitations, institutional factors, organisational challenges, and social and cultural norms (Hazarika & Zhang, 2019). Despite the value added by cold chain e-fulfilment to the retail e-commerce business, the industry's heavy reliance on energy and resources has resulted in significant carbon emissions, waste generation, and environmental pollution, potentially undermining the industry's long-term sustainability. The potential conflict between economic growth and environmental sustainability necessitates identifying eco-innovation barriers that hinder the sustainable development of the cold chain e-fulfilment system.

While previous studies have contributed to effective cold chain fulfilment by focusing on quality and safety issues (Robertson et al., 2017; Tsang et al., 2020; Ye et al., 2022), among others, and eco-innovation practices in the cold chain (Dai et al., 2020; Mylan et al., 2015), less attention has been given to identifying eco-innovation barriers specific to cold chain e-fulfilment. Given the current global energy shortage and the urgent need to address climate change, it is crucial to identify and overcome these barriers in cold chain e-fulfilment systems. Such efforts improve operational efficiency and contribute to broader sustainability goals, supporting global initiatives to mitigate climate change. Therefore, theoretical considerations and practical demands drove this study to establish a systematic analysis framework for eco-innovation barriers, aiming to identify underlying barriers in cold chain e-fulfilment systems and provide recommendations for sustainable solutions. In this context, the following research questions (RQs) are addressed in this study:

1. RQ1: What are the barriers hindering the implementation of eco-innovation practices in cold chain e-fulfilment systems?
2. RQ2: What is the prominence level of these barriers in cold chain e-fulfilment systems?
3. RQ3: How can stakeholders mitigate the eco-innovation barriers?

In order to address the RQs, this study conducted a literature review and expert interviews using the sustainability transition analysis framework (STAF) to identify significant barriers hindering eco-innovation adoption in cold chain e-fulfilment. Given that mitigating all of the barriers simultaneously is not feasible, prioritising the barriers becomes crucial for successful eco-innovation implementation. This prioritisation allows stakeholders in the e-commerce cold chain to develop an implementation plan by first addressing the highly prioritised barriers and optimising their resources for barrier mitigation. This study utilises the group decision-making fuzzy best worst method (GDM-FBWM) to prioritise these barriers.

This study contributes to three key aspects. Firstly, it introduces a formal framework for the comprehensive identification and prioritisation of eco-innovation barriers, specifically in the cold chain e-fulfilment process, representing the first exploration within this research domain. Secondly, it extends the best worst method (BWM) by incorporating group decision-making (GDM) capabilities within a fuzzy decision-making environment to tackle practical barrier analysis problems. This extension provides a feasible technique that practitioners can apply. Thirdly, the study offers potential solutions to the identified barriers. The research aims to provide valuable insights and inspire industrial practitioners by discussing these solutions.

The remaining sections of this paper are organised as follows. The second section provides a review of related work in the areas of cold chain e-fulfilment and decision techniques for barrier analysis problems. In the next section, the proposed methodology is described in detail. The fourth section presents the application process of identifying barriers and determining their prominence degree using the GDM-FBWM approach. The results are discussed in the fifth section, offering valuable insights and analysis. Finally, the last section summarises the conclusions drawn from this study and outlines potential directions for future research.

RELATED WORK

Cold Chain E-Fulfilment System and Operations

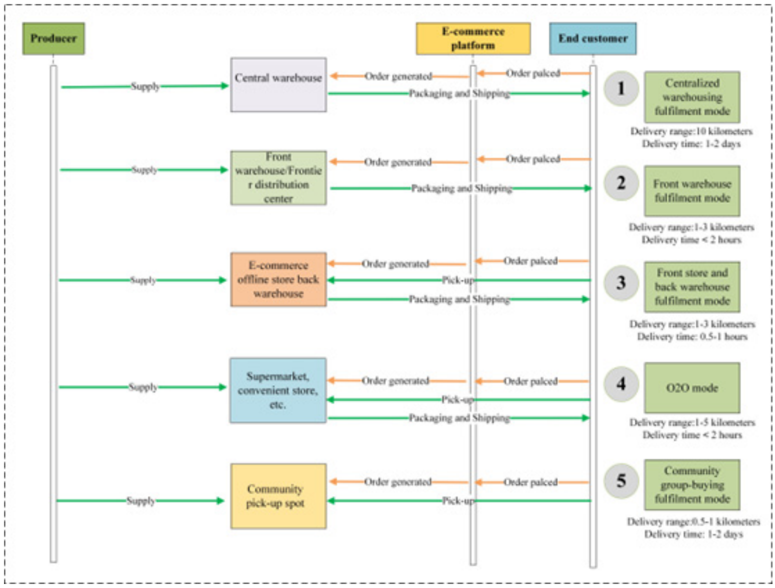
Differing from classical e-fulfilment systems and traditional brick-and-mortar channels, the cold chain e-fulfilment system comprises various operational models due to strict requirements for timeliness, product quality, cold storage facilities, refrigerated transportation, and packaging (Agatz et al., 2008; Shih & Wang, 2016; Yakzan & Nelson, 2015). The cold chain e-fulfilment system is designed to connect each node of the cold chain to maintain the integrity of the temperature-controlled supply chain, from manufacturing to delivery to the end customer. In terms of the temperature monitoring and control system, sensors and data loggers are used to monitor and adjust the temperature of the shipped products, ensuring they remain within the required temperature range (Tsang et al., 2017). Inventory management typically applies the first-expired-first-out strategy to manage outbound goods, reducing costs by avoiding waste and ensuring consistent quality (Jedermann et al., 2014; Mercier et al., 2017). The warehouse management system manages the storage and movement of temperature-sensitive products in the fulfilment centre. It includes managing temperature-controlled storage areas, monitoring environmental conditions, and tracking product expiration dates. Efficient cold chain management also requires robust quality control processes to meet product quality and safety standards, ensuring products are free from contamination, spoilage, and other defects (Laguerre et al., 2013). E-commerce platforms are critical in enabling customers to interact with the cold chain e-fulfilment process by facilitating product ordering, tracking deliveries, and providing feedback. By offering real-time temperature tracking and monitoring information, e-commerce platforms can build trust and confidence in their services, increasing customer loyalty and repeat business (Kelepouris et al., 2007).

Previous research has identified different e-fulfilment operations that deliver products to customers, organising the process from order intake to delivery. Researchers have proposed typologies of order fulfilment modes based on the location where orders are prepared and the delivery method to customers (De Koster, 2002; Durand & Gonzalez-Feliu, 2012; Lang & Bressolles, 2014). In the context of cold chain e-fulfilment, there is a wide range of order fulfilment modes. Many e-commerce platforms are opening physical stores or pickup points where customers can interact and collect items to reduce last-mile delivery costs and enhance offline customer experiences (Lang & Bressolles, 2014). Additionally, regional lockdowns and social distancing measures have accelerated the shift from offline to online commerce, leading fresh producers to focus on local communities. E-commerce giants are partnering with local farmers and suppliers to promote the development of fresh e-commerce models in the community, resulting in the community cold chain e-fulfilment operation mode (Ong & Lee, 2020). This mode involves forming a community or group of buyers to purchase products in bulk at an economy of scale. For warehouse management, e-commerce companies have adopted the business model of a frontier distribution centre and back warehouse (i.e., distributed mini warehouses) to minimise delivery time and ensure product freshness by reducing the distance between products and target customers.

Furthermore, unsuccessful last-mile deliveries result in returned shipments, increasing operational complexity (Jiang et al., 2021). To optimise product quality and delivery costs, self-service pickup point systems such as nearby supermarkets, community convenience stores, and even fresh food producers are commonly used as another order fulfilment mode (Shih & Wang, 2016). In light of the abovementioned circumstances, Figure 2 summarises five typical cold chain e-fulfilment operation modes, from order intake to delivery. However, it is worth noting that integrating eco-innovation concepts into cold-chain e-fulfilment remains largely unexplored.

Cold chain e-fulfilment, due to the nature of temperature-sensitive products and the high demand driven by e-commerce, presents unique challenges and complexities. These challenges include increased energy consumption (Allen et al., 2018; Ruan & Shi, 2016), the integration of decentralised information systems (Q. Chen et al., 2022), consensus on low-carbon practices (Q. Chen et al., 2022),

Figure 2. Five typical operation modes of cold chain e-fulfilment



policy responses (Q. Chen et al., 2022; G. Singh et al., 2022), and the potential paradox between achieving efficient cold chain operations and environmental sustainability (Adekomaya et al., 2016; Q. Chen et al., 2022). The energy-intensive nature of cold chain operations, including refrigeration and transportation, can have significant environmental implications (Tsang et al., 2017). Ruan and Shi (2016) pointed out that in e-retailing, the delivery of fresh produce is quite different from traditional transportation. Meanwhile, different kinds of fresh produce have specific characteristics in e-fulfilment. From a macro level, Q. Chen et al. (2022) argued the necessity of exploring the development innovation in this domain towards sustainability. Eco-innovation offers a potential solution by promoting the development and adoption of sustainable practices and technologies (Afshari et al., 2020). However, the complexity of cold chain e-fulfilment, with its intricate modes of operation and specific product characteristics, has introduced additional challenges to eco-innovation (Q. Chen et al., 2022). Within this context, exploring these potential barriers is crucial to overcoming challenges and finding viable solutions that reconcile customer demand with environmental considerations in cold chain e-fulfilment.

Multi-Criteria Decision-Making for Barrier Evaluation and Prioritisation

Assessing and prioritising the barriers can be regarded as a discrete multi-criteria decision-making (MCDM) problem (Z.-S. Chen et al., 2024). Among various MCDM techniques, the BWM proposed by Rezaei (2015) has emerged as a promising approach in this domain. This method facilitates evaluating and prioritising alternatives based on multiple criteria, considering the relative importance of each criterion. The implementation procedure of the BWM entails the selection of the best and worst criteria from a predefined set. Subsequently, a comparison is made between the best criterion and all other criteria, as well as between the worst criterion and all other criteria, resulting in a pairwise comparison matrix. The weights of the criteria can be determined through a linear optimisation model. Several scholars have suggested that the BWM yields more robust and reliable outcomes than similar MCDM approaches (Guo & Zhao, 2017; S. Khan et al., 2023; Rezaei, 2015). The effectiveness and robustness of the BWM have been demonstrated in recent years, particularly in prioritising factors, barriers, and enablers (S. Khan et al., 2023; P. K. Singh & Maheswaran, 2024).

Table 1. Application of BWM in the barrier analysis

Authors	*Nature of contribution*
Orji et al. (2019)	The challenges of implementing eco-innovation for freight logistics sustainability
D. Chen et al. (2020)	The evaluation of the critical barriers and pathways to implementation of e-waste formalisation management systems
Mahmud et al. (2021)	The barriers to supply chain collaboration in SMEs
M. I. Khan et al. (2022)	The barriers towards management of the Halal supply chain
Heidary-Dahooie et al. (2022)	The prioritisation for blockchain adoption barriers in the supply chain
Wei et al. (2023)	The barriers to forest carbon sink project implementation in China
S. Khan et al. (2023)	The barriers to blockchain technology integrated food supply chain
Srinivasan et al. (2023)	The assessment of mitigation strategies for lean and green barriers in the food supply chain
P. K. Singh & Maheswaran (2024)	The social barriers to sustainable innovation and digitisation in the supply chain
Panigrahi et al. (2024)	The barriers to the green supply chain management adoption in the Indian aluminium sector
Agyekum (2024)	The opportunities and barriers of hydrogen production on the continent

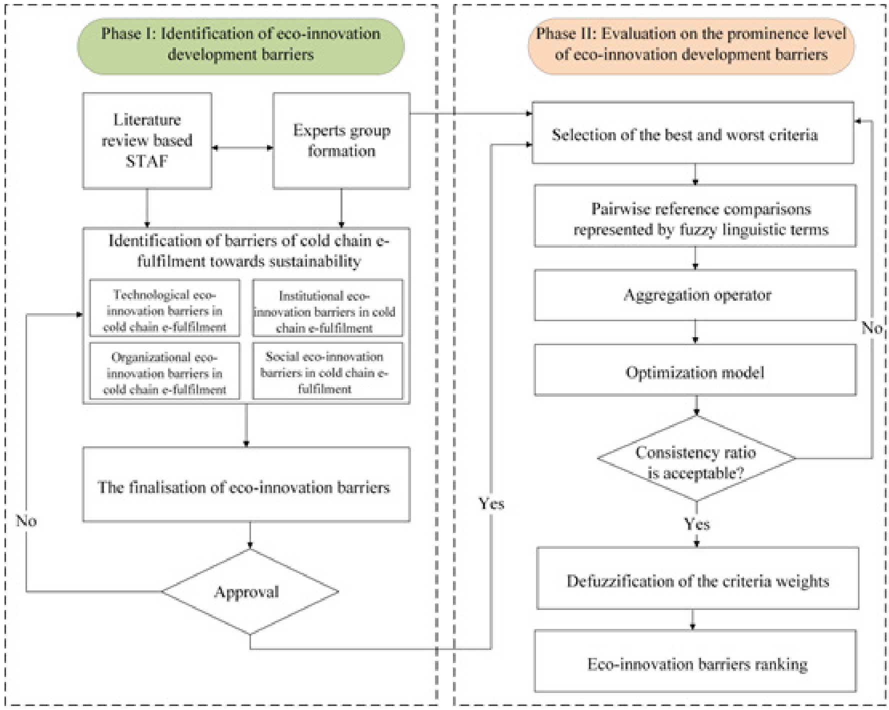
Table 1 summarises the applications of BWM-based research in barrier analysis, showcasing its capability in evaluating and prioritising specific barriers.

While the structured pairwise comparison approach in the BWM can provide reliable support for modeling the subjective decision-making process of humans (Wu et al., 2024), some scholars have pointed out that using crisp values to represent the preferences of decision-makers (DMs) may oversimplify the inherent complexity and uncertainty of human subjective decision-making (Guo & Zhao, 2017; Irannezhad et al., 2021). In real-life decision-making processes involving human experts, fuzzy set theory, proposed by Zadeh (1965), is an effective approach to address the ambiguity and uncertainty associated with expert judgement. The integration of fuzzy set theory and the BWM can facilitate the aggregation of individual opinions by quantifying subjective assessments more flexibly and inclusively (Mostafaeipour et al., 2021). It allows DMs to express their evaluations using linguistic terms, enabling a more comprehensive and realistic representation of their preferences (Guo & Zhao, 2017; P. Wang et al., 2023). Therefore, integrating fuzzy set theory into the BWM is a feasible solution to better capture human experts' preferences. Several existing studies have demonstrated the feasibility and robustness of this integrated approach in the barrier analysis problem within the fuzzy GDM environment (Heidary-Dahooie et al., 2022; Mostafaeipour et al., 2021; Srinivasan et al., 2023). Within this context, further exploration and adaptation of integrating fuzzy set theory with the BWM in the GDM environment can be pursued, particularly in the cold chain e-fulfilment domain.

Summary

Despite previous studies on cold chain management related to improving the efficiency of cold chain e-fulfilment (Bottani et al., 2019; Ruan & Shi, 2016; Tsang et al., 2017; Vrat et al., 2018), there is a noticeable lack of research exploring the potential eco-innovation barriers in cold chain e-fulfilment. This gap results in insufficient insights into promoting sustainable practices during the sustainability transition in the cold chain e-fulfilment domain. Bridging this gap is crucial, especially considering the global sustainable development goals (SDGs). Furthermore, previous studies that have explored barriers in supply chain scenarios have demonstrated the effectiveness and reliability of the BWM. However, in the decision-making process involving multiple DMs, it is believed that

Figure 3. Analysis framework for identifying and prioritising eco-innovation development barriers in cold chain e-fulfilment



providing linguistic preferences rather than crisp numbers for judgement is more reasonable and reliable in MCDM problems. Therefore, the classic BWM can be further extended by incorporating a fuzzy GDM capability to aggregate different expert opinions intelligently. Therefore, this paper aims to develop a comprehensive and robust analysis framework that explores and prioritises eco-innovation barriers in cold chain e-fulfilment from a sustainability transition perspective in the fuzzy GDM environment.

METHODOLOGY

The primary goal of this research is to identify the critical barriers to eco-innovation development in cold chain e-fulfilment and investigate their levels of prominence. These barriers are identified through a literature review and supported by domain experts' opinions in the industry and academia. Additionally, the FBWM modelling framework based on the GDM is proposed to rank the identified barriers. The reliability of the results is evaluated using consistency ratios (CRs). The entire methodological process is illustrated in Figure 3.

Extraction of the Eco-Innovation Barriers in Cold Chain E-Fulfilment System

To fully understand the eco-innovation barriers in cold chain e-fulfilment and their impact on sustainability, it is essential to explore these barriers. This exploration can contribute to reducing the environmental impact, informing policy and regulatory initiatives, and identifying opportunities for innovation and improvement. In order to facilitate this exploration and identify the crucial factors for the sustainability transition, Hazarika and Zhang (2019) proposed a comprehensive analysis framework known as the STAF. The STAF consists of four dimensions of eco-innovation: technological eco-innovation, institutional eco-innovation, organisational eco-innovation, and social eco-innovation. These dimensions can be used to examine the achievement of sustainability transition in various contexts. Considering the relevance of the STAF to this study and its alignment with the evolving theories of eco-innovation, it is adopted in this research to explore the four dimensions of eco-innovation barriers in cold chain e-fulfilment.

The selection of the barriers involved two parts. In the initial phase, keywords aligned with the research topic, such as ‘eco-innovation’, ‘e-commerce cold chain’, ‘cold chain e-fulfilment’, ‘sustainable development’, ‘sustainability transition’, ‘barrier’, and ‘challenge’, were determined. Additionally, it is important to focus on specific eco-innovation dimensions, namely ‘technological eco-innovation’, ‘institutional eco-innovation’, ‘organisational eco-innovation’, and ‘social eco-innovation’. Therefore, terms such as ‘technological’, ‘technology’, ‘institutional’, ‘policy and regulation’, ‘organisational’, and ‘social’ can be valuable reference points for identifying specific barriers. The second phase involves keyword searches in Web of Science and Google Scholar over the past decade. These databases are widely used, have broader journal coverage, and include many recent publications (Z.-S. Chen et al., 2024). The search terms used in the database search encompass a range of topics, including ‘cold chain e-fulfilment eco-innovation barrier’, ‘e-commerce cold chain eco-innovation barrier’, ‘cold chain sustainability transition barrier’, ‘cold chain sustainable development barrier’, ‘sustainable e-commerce cold chain’, ‘e-commerce cold chain sustainable challenges’, ‘e-commerce cold chain technological eco-innovation’, ‘e-commerce cold chain policy and regulation’, ‘e-commerce cold chain social sustainability’, ‘e-commerce cold chain operation and organisation management’, ‘e-commerce cold chain eco-innovation challenges’, and ‘sustainable cold chain e-fulfilment challenges’, resulting in nine documents. We also conducted a similar search using the same keywords in Google Scholar, which yielded three more articles related to our research topic. These 12 articles were examined in detail for their relevance to our study. Following the dimensions of the STAF, the barriers were further categorised into four aspects: technological eco-innovation, institutional eco-innovation, organisational eco-innovation, and social eco-innovation. These preliminary barriers were identified through an extensive literature review and were presented to invited experts for their opinions. Based on their industrial experience, the experts would help identify and finalise the barriers. If all of the experts agreed that the identified barriers were relevant to the current study, these barriers would be finalised for further data collection and analysis.

Previous research on barrier evaluation and prioritisation has demonstrated the effective utilisation of MCDM techniques with a limited sample size, enabling consistency and realistic results (Z.-S. Chen et al., 2024; S. Khan et al., 2023; P. K. Singh & Maheswaran, 2024). In order to ensure the robustness of decision-making based on expert opinions in this study, industrial experts were required to possess a minimum of five years of practical experience in the domains of supply chain, cold chain, or e-commerce fulfilment. Similarly, for academic experts, specialisation in logistics, the cold chain, or the e-commerce supply chain was one of their research areas. Furthermore, the selected experts needed to possess a comprehensive understanding of the research objectives. A questionnaire was administered to gather the experts’ opinions through pairwise comparisons, allowing them to weigh the significance of different barriers. The barriers confirmed through this process could be sorted and finalised for further evaluation by incorporating the experts' opinions.

Evaluation of the Prominence Level of Barriers

As mentioned earlier, the BWM has effectively assigned weights to selected barriers in MCDM scenarios. However, there is a limitation to this method. It relies on crisp values from one to nine to express DMs’ preferences, which makes it unreliable in uncertain decision-making environments (Ghoushchi et al., 2019; Guo & Zhao, 2017). The qualitative judgement represented by crisp values may not adequately address challenges arising in real-life decision-making due to uncertainty and ambiguity (Ghoushchi et al., 2019). Recent research has shown that the Type-1 Fuzzy Best Worst Method (T1-FBWM) is more effective in handling human judgement results (Guo & Zhao, 2017; Irannezhad et al., 2021). T1-FBWM extends the BWM by considering uncertainty and ambiguity in

Table 2. Transformation rules of linguistic variables

Linguistic terms	*Triangular fuzzy numbers*
Equally important (EI)	(1,1,1)
Weakly important (WI)	(2/3,1,3/2)
Fairly important (FI)	(3/2,2,5/2)
Very important (VI)	(5/2,3,7/2)
Absolutely important (AI)	(7/2,4,9/2)

the decision-making process. It allows individuals to evaluate options based on their perceived best and worst attributes and considers the degree of uncertainty associated with each evaluation. While T1-FBWM was initially used for individual decision-making, the GDM is increasingly important in today's rapidly changing and complex decision-making environments. Decisions often involve multiple stakeholders with different perspectives, requiring balancing multiple criteria and trade-offs (Huang et al., 2023). Therefore, in this study, the GDM-FBWM is developed to navigate such complex decision-making environments.

To conduct the GDM-FBWM, the four dimensions of barrier criteria, $\{C_1, C_2, C_3, C_4\}$, and the criteria within each dimension, $\{C_{11}, C_{12}, \cdots\ C_{1n}\}$, $\{C_{21}, C_{22}, \cdots\ C_{2n}\}$, $\{C_{31}, C_{32}, \cdots\ C_{3n}\}$, and $\{C_{41}, C_{42}, \cdots\ C_{4n}\}$, are defined based on the literature review and expert feedback. With the help of the expert group, the best and worst dimensions and eco-innovation barriers can be determined. Each expert is then required to conduct pairwise reference comparisons of the best criterion to others and others to the worst criteria using linguistic variables, as shown in Table 2. The experts' linguistic assessments can be modeled using triangular fuzzy numbers. The preference comparisons are expressed through the Best-to-Others vector $\widetilde{C}_B = \{\widetilde{C}_{B1}, \widetilde{C}_{B2}, \cdots\ \widetilde{C}_{Bn}\}$ and Others-to-Worst vector $\widetilde{C}_W = \{\widetilde{C}_{1W}, \widetilde{C}_{2W}, \cdots\ \widetilde{C}_{nW}\}$. The experts' preferences are then aggregated using the geometric mean method to incorporate the GDM capability of BWM into the process. Assuming there are q experts, the final aggregated vector for the Best-to-Others comparison is presented as $\widetilde{a}_{Bj} = \left(\widetilde{a1}_{Bj} \otimes \widetilde{a2}_{Bj} \otimes \cdots \otimes \widetilde{aq}_{Bj}\right)^{1/q}$, where $\widetilde{a}_{Bj}$ refers to the preference of the best criterion over the other criteria and $\widetilde{a}_{BB} = (1,1,1)$. Finally, a linear optimisation model is formulated to determine the optimal weight $\widetilde{w}_i$ for each criterion. The weight of each criterion is represented as $\widetilde{w}_j = (l_j^w, m_j^w, u_j^w)$. The objective of this model is to minimise the absolute difference $\widetilde{\xi}$, subject to the corresponding constraints: (i) $|\widetilde{\varpi}_B - \widetilde{a}_{Bj}\widetilde{\varpi}_j| \le \widetilde{\xi}$, (ii) $|\widetilde{\varpi}_j - \widetilde{a}_{jW}\widetilde{\varpi}_W| \le \widetilde{\xi}$, (iii) $\sum_j R(\widetilde{\varpi}_j) = 1$, and (iv) $0 \le l_j^\omega \le m_j^\omega \le u_j^\omega$, where $j \in [1, n]$.

Validation of the Consistency Ratios

To validate the reliability of the computed results, the CR is calculated based on the pairwise comparison results to assess the consistency level of the DMs. In ideal circumstances, when the fuzzy comparisons are fully consistent, $\widetilde{a}_{Bj} \times \widetilde{a}_{jW} = \widetilde{a}_{BW}$ for all j. However, there may be some inconsistencies in the decision-making process in practice. Therefore, an output-based CR, $CR = \xi / Consistency\ index$, is proposed to evaluate the degree of consistency in the FBWM. The maximum value $\widetilde{\xi}$ is used as the consistency index, obtained by substituting the maximum possible value of a $\widetilde{a}_{BW}$ into the equation $\widetilde{\xi}^2 - (1 + 2 * \widetilde{a}_{BW}) * \widetilde{\xi} + (\widetilde{a}_{BW}^2 - \widetilde{a}_{BW}) = 0$. The CR ranges between zero and one, with a value close to zero indicating a high level of consistency in expert assessments and acceptable results. To determine the corresponding thresholds of output-based CRs, refer to the work of Liang et al. (2020). The crisp value of each criterion's weight can then be transformed using $R(\widetilde{w}_j) = (l_j^w + 4 * m_j^w + u_j^w)/6$.

APPLICATION OF THE PROPOSED ANALYSIS FRAMEWORK

Cold Chain E-Fulfilment Barriers

Based on the methodology proposed in this study, 17 barriers were finally determined through a literature review and expert opinions, which are presented in Table 3. The 17 identified barriers were further categorised into four dimensions: technological eco-innovation, institutional eco-innovation, organisational eco-innovation, and social eco-innovation.

Technological Eco-Innovation Dimension

Technological eco-innovation encompasses developing and integrating innovative technologies that aim to reduce carbon emissions and enhance efficiency (Ma & Mo, 2023; Tsang et al., 2017). In the context of cold chain e-fulfilment, a technological eco-innovation approach requires balancing resource costs and GHG emissions costs when considering the technology used to maintain product quality and safety (Q. Chen et al., 2022). One major obstacle in achieving cold chain sustainability from a technological standpoint is the high implementation costs. Using energy-efficient equipment and eco-innovation technologies, such as smart sensors and real-time data analysis, can contribute to optimising energy usage in cold chain e-fulfilment. However, the costs associated with implementing new technologies and eco-innovation solutions can pose significant barriers, particularly for small and medium-sized enterprises (SMEs). Moreover, integrating new technologies and eco-innovation solutions with existing legacy systems can be challenging and time-consuming, especially if the systems were not originally designed to work together (G. Singh et al., 2022).

Additionally, some new technologies and eco-innovation solutions may face difficulties in scaling up to meet the demands of large-scale operations, which can limit their effectiveness in cold chain e-fulfilment. Furthermore, utilising new technologies and eco-innovation solutions necessitates effective data management, including collecting, analysing, and sharing data among e-commerce cold chain partners. This can present challenges, particularly when dealing with substantial amounts of data in complex e-commerce cold chains that incorporate hybrid business models.

Institutional Eco-Innovation Dimension

Institutional eco-innovation focuses on policies and regulations promoting sustainable industry practices. A complex regulatory framework can pose a significant barrier to eco-innovation in cold chain e-fulfilment, as it introduces uncertainties and ambiguities for companies, impeding their ability to make informed decisions and invest in sustainable practices (Polzin, 2017). Gupta and Barua (2018) highlight that the varying and complex regulatory frameworks across different countries can lead to a lack of clear guidance on adopting eco-innovation for achieving sustainability. Furthermore, a lack of incentives presents another challenge within this dimension. Often, there is a scarcity of financial incentives for companies to adopt more sustainable practices in cold chain e-fulfilment, which can discourage investment in eco-innovation. Additionally, the legal framework concerning data privacy and security issues for adopting eco-innovation is still inadequately established (G. Singh et al., 2022). In an efficient cold chain e-fulfilment system, various machines, sensors, facilities, and humans are interconnected via the internet, exchanging data. Legal issues, such as data privacy and security, need to be considered when adopting modern technology to develop data-driven sustainable business models (Luthra & Mangla, 2018; Muller et al., 2017). Moreover, a lack of clear metrics and standards for measuring the environmental impact of cold chain e-fulfilment can make it challenging for organisations to set targets and track progress towards sustainability goals (G. Singh et al., 2022).

Organisational Eco-Innovation Dimension

Organisational eco-innovation focuses on internal organisational practices and structures. Organisations need to adopt an innovative approach to their business operations to achieve sustainable development. The support and dedication of management in advocating eco-innovation are crucial for developing effective sustainable practices. However, resistance to change within organisations can arise, especially when existing practices are perceived as effective and efficient, making it challenging to implement more sustainable alternatives (G. Singh et al., 2022). Additionally, implementing eco-innovative practices in cold chain e-fulfilment often requires substantial investments in technology, infrastructure, and human resources, which can be a barrier, particularly for SMEs. Moreover, a lack of expertise within organisations on sustainable cold chain e-fulfilment practices can make it difficult to identify and implement eco-innovative solutions. Therefore, organisations should enhance their eco-innovation capabilities through employee training and development programs and knowledge management initiatives (Luthra & Mangla, 2018).

Furthermore, the support and dedication of management are essential for the successful implementation of eco-innovation (Q. Chen et al., 2022). Without proper dedication, eco-innovation initiatives may be perceived as unnecessary costs and not given the necessary priority. Therefore, addressing the barrier of low management support and dedication is critical for successfully implementing sustainable practices in cold chain e-fulfilment, requiring top-level management to prioritise sustainability and allocate the necessary resources to eco-innovation initiatives.

Social Eco-Innovation Dimension

Social eco-innovation encompasses stakeholder engagement, education, and communication, which are crucial in driving sustainable practices. However, stakeholders' lack of awareness and education regarding the environmental impact of cold chain e-fulfilment and the potential benefit of eco-innovation makes it challenging for businesses to justify the cost of implementing such solutions. This is because consumers may not be willing to pay more for sustainable products or services, which hinders the adoption of more sustainable practices (Orji et al., 2019). Limited engagement with stakeholders, including consumers, non-governmental organisations (NGOs), and others, can restrict understanding of the environmental impact of cold chain e-fulfilment and the potential of eco-innovation solutions. Effective communication and engagement are crucial to ensuring that stakeholders understand the importance of eco-innovation practices and the benefits they can bring (Luthra & Mangla, 2018). For example, manufacturers may not be aware of the environmental impact of their packaging materials or the potential benefits of using eco-friendly alternatives. Logistics companies may lack access to the latest technologies or best practices for reducing carbon emissions during transportation and warehousing.

Additionally, consumer preferences and behaviour can prevent adopting more sustainable cold chain e-fulfilment practices. Consumers may prioritise speed and convenience over sustainability. Moreover, there may be a lack of trust among consumers and other stakeholders regarding the sustainability claims of organisations involved in cold chain e-fulfilment, which can hinder the adoption of more eco-innovative practices. Furthermore, there may be a perception among consumers and organisations that eco-innovative solutions in cold chain e-fulfilment are more expensive, which can discourage investment in sustainable practices (Q. Singh et al., 2022; Van der Merwe et al., 2013).

Evaluation of the Prominence Level

The previous section identified 17 underlying development barriers to eco-innovation in sustainable cold chain e-fulfilment based on a literature review and expert interviews. In this section, we evaluate the importance level of eco-innovation dimensions and the prominence level of each barrier using the GDM-FBWM. Previously published studies have widely used BWM and its extension, the FBWM, in various fields to address MCDM problems and provide accurate results with small sample sizes (M. I. Khan et al., 2022; Moktadir et al., 2018; Orji et al., 2019; Yazdani et al., 2022). For example, Moktadir et al. (2018) applied the BWM to identify potential crucial challenges for implementing Industry 4.0 in the leather industry. The study involved a sample size of eight experts, and the BWM yielded reliable results in identifying the most important indicators.

Table 3. Eco-innovation barriers under the STAF

Dimensions	*Identified barriers*	*References*
Technological eco-innovation (T)	High implementation costs (T1)	Yu et al. (2016); Allen et al. (2018); Kiefer et al. (2018); Cichosz et al. (2020); Tsang et al. (2020); G. Singh et al. (2022)
	Integration with legacy systems (T2)	
	Limited scalability (T3)	
	Data management (T4)	
Institutional eco-innovation (I)	Complex regulatory frameworks (I1)	Bai & Guo (2017); Janjevic and Winkenbach (2020); G. Singh et al. (2022)
	Lack of incentives (I2)	
	Legal issues such as data privacy and security (I3)	
	Lack of eco-innovation metrics and standards (I4)	
Organisational eco-innovation (O)	Reluctant behaviour towards eco-innovation (O1)	Allen et al. (2018); Kiefer et al. (2018); Janjevic and Winkenbach (2020); Cichosz et al. (2020)
	Financial constraints (O2)	
	Lack of training and development expertise (O3)	
	Low management support and dedication (O4)	
Social eco-innovation (S)	Limited awareness and education on eco-innovation (S1)	Van der Merwe et al. (2013); Bag (2016); Allen et al. (2018); Luthra and Mangla (2018); G. Singh et al. (2022)
	Limited stakeholder engagement and communication (S2)	
	Consumer preferences and behaviour (S3)	
	Lack of trust (S4)	
	Perception of cost (S5)	

Similarly, in the study conducted by Yazdani et al. (2022), the FBWM was used to measure resiliency performance in the food supply chain by considering the uncertainty and fuzziness of the experts' judgements. In this current study, we surveyed 14 experts from the related industry and academia to gather their opinions on eco-innovation practices in sustainable cold chain e-fulfilment and to assess the severity of eco-innovation barriers. Table 4 presents the demographic characteristics of the experts.

Following the procedures of the GDM-FBWM as demonstrated previously, pairwise comparisons based on the four eco-innovation dimensions were conducted to determine their importance levels. The data for these comparisons were collected through a questionnaire survey designed following the FBWM style. Before completing the survey, the purpose and content of the survey were explained to the experts. A pre-survey briefing was conducted to ensure that all respondents understood and were familiar with the survey instrument. The experts were then asked to identify the best and worst dimensions among the four categories. After each expert had chosen the best and worst dimensions, they were requested to provide preference ratings of 'Best-to-Others' and 'Others-to-Worst' for each dimension using linguistic preference terms.

Similarly, the experts were also asked to select the best and worst criteria within each eco-innovation dimension and rate them accordingly. Table 5 and Table 6 present the best and worst dimensions and criteria identified by the 14 experts. Once the ratings from the 14 experts were obtained, the next step was synthesising the group opinions using the geometric mean method. The importance weight of each eco-innovation dimension and the eco-innovation barriers within each dimension were calculated following the procedures outlined previously. Furthermore, the global importance weight was computed by combining the main dimension's importance with each eco-innovation barrier's

Table 4. Profile of the invited experts

Code	*Highest academic qualification*	*Position*	*Domain/area*	*Experience*
E1	Doctor of Philosophy	Data Scientist	Digital Transformation of Logistics Industry	6 Years
E2	Master of Business Administration	Vice President	Cold Chain Logistics Network for Commercial Services	17 Years
E3	Doctor of Administration	Chief Operations Officer	E-Business and International Trade	24 Years
E4	Doctor of Philosophy	Senior Lecturer	Supply Chain Management	11 Years
E5	Doctor of Philosophy	Associate Professor	Smart Logistics	13 Years
E6	Doctor of Philosophy	Research Assistant Professor	Cold Chain and E-Commerce Logistics Management	9 Years
E7	Bachelor of Engineering	Senior Product Manager	E-Commerce Platform Design and Integration	10 Years
E8	Doctor of Philosophy	Lecturer	Digital Transformation and Logistics Technology	6 Years
E9	Bachelor of Business Administration	Consultant	Supply Chain Solution	6 Years
E10	Master of Art	Project Assistant	E-Commerce Platform Operation	5 Years
E11	Bachelor of Engineering	Warehouse Operation Manager	Logistic Service	18 Years
E12	Master of Science	Procurement Manager	Fresh Food E-Commerce	8 Years
E13	Master of Science	Growth Marketing Manager	Supply Chain Service	11 Years
E14	Bachelor of Engineering	Senior Merchant Success Manager	Cold Chain E-Commerce	13 Years

local importance weight. These weights were then used to rank each eco-innovation barrier. The calculated weight, global weight, and rank are presented in Table 7.

The GDM-FBWM analysis provides the importance levels of the eco-innovation dimensions in eco-innovation-oriented cold chain e-fulfilment as determined by their importance weights: 'social eco-innovation' ≻ 'technological eco-innovation' ≻ 'institutional eco-innovation' ≻ 'organisational eco-innovation'. Within the dimension of social eco-innovation, the analysis revealed that the most significant barrier to developing eco-innovation-oriented cold chain e-fulfilment was 'limited stakeholder engagement and communication (S2)', followed by 'limited awareness and education on eco-innovation (S1)' and 'consumer preferences and behaviour (S3)'. Conversely, 'lack of trust (S4)'

Table 5. The best and worst dimensions determined by experts

Dimensions	*Determined as the best by experts*	*Determined as the worst by experts*
Technological eco-innovation	E6, E7, E8, E11, E13	E1
Institutional eco-innovation		E2, E7, E9, E10, E12, E13, E14
Organisational eco-innovation		E3, E4, E5, E6, E8
Social eco-innovation	E1, E2, E3, E4, E5, E9, E10, E12, E14	E11

Note. This table presents the judgements of 14 experts (each expert identified by a unique identifier code *Ei*, where *i* =1, 2, ..., 14) regarding the best and worst dimensions/criteria.

Table 6. The best and worst criteria determined by experts

Barriers	*Determined as the best by experts*	*Determined as the worst by experts*
T1	E4, E6, E9, E13, E14	
T2	E1, E2, E3, E8, E10, E11, E12	
T3	E5	E4, E7, E8, E13
T4	E7	E1, E2, E3, E5, E6, E9, E10, E11, E12, E14
I1	E1, E2, E4, E7, E8, E10, E11, E12, E13	E9
I2		E2, E3, E7, E8, E11, E12, E14
I3		E4, E5, E6, E10, E13
I4	E3, E5, E6, E9, E14	E1
O1		E4, E5, E7, E10, E11
O2	E1, E3, E4, E5, E7, E8, E9, E12, E14	E2
O3		E3, E6, E8, E9, E12, E13, E14
O4	E2, E6, E10, E11, E13	E1
S1	E1, E10	
S2	E2, E3, E5, E6, E9, E12, E13, E14	
S3	E4, E11	E5, E7, E10
S4	E7	E1, E4, E8, E9, E14
S5	E8	E2, E3, E6, E11, E12, E13

Note. This table presents the judgements of 14 experts (each expert identified by a unique identifier code *Ei*, where *i* =1, 2, ..., 14) regarding the best and worst dimensions/criteria.

and ‘perception of cost (S5)’ were less significant than other social eco-innovation barriers. For the barriers within the technological eco-innovation dimension, the importance order was ‘integration with legacy systems (T2)’ ≻ ‘high implementation costs (T1)’ ≻ ‘limited scalability (T3)’ ≻ ‘data management (T4)’. Regarding the eco-innovation barriers within the institutional eco-innovation dimension, ‘complex regulatory frameworks (I1)’ was considered the most critical barrier, followed by ‘lack of eco-innovation metrics and standards (I4)’, ‘lack of incentives (I2)’, and ‘legal issues such as data privacy and security (I3)’. Within the organisational eco-innovation dimension, the importance order was ‘financial constraints (O2)’ ≻ ‘low management support and dedication (O4)’ ≻ ‘lack of training and development expertise (O3)’ ≻ ‘reluctant behaviour towards eco-innovation (O1)’. Furthermore, the global weights of the eco-innovation development barriers were ranked, as shown in Table 6. The top four eco-innovation development barriers in developing sustainable cold chain e-fulfilment were ‘integration with legacy systems (T2)’, ‘high implementation costs (T1)’, ‘limited stakeholder engagement and communication (S2)’, and ‘limited awareness and education on eco-innovation (S1)’.

Consistency Level Validation

Consistency level measurement is important to ensure that the judgements made in the pairwise comparison matrix are consistent and reliable (Rezaei, 2016). In order to assess the consistency of judgements provided by experts in the GDM-FBWM, the results of pairwise comparisons for the four dimensions were validated. In this round of pairwise comparisons, the computed ξ value was 0.1284. Based on the threshold for output-based consistency measurement (Liang et al., 2020), which is around 0.2848 for an evaluation grade scale close to five and four criteria, the computed weight

Table 7. Final ranking of eco-innovation dimensions and barriers

Dimensions	*Weights*	*Barriers*	*Local weight*	*Local rank*	*Global weight*	*Global rank*
Technological	0.313	T1	0.327	2	0.102	2
		T2	0.377	1	0.118	1
		T3	0.155	3	0.049	10
		T4	0.142	4	0.044	11
Institutional	0.183	I1	0.340	1	0.062	6
		I2	0.185	3	0.034	14
		I3	0.159	4	0.029	15
		I4	0.317	2	0.058	7
Organisational	0.157	O1	0.143	4	0.022	17
		O2	0.363	1	0.057	8
		O3	0.178	3	0.028	16
		O4	0.316	2	0.050	9
Social	0.347	S1	0.243	2	0.084	4
		S2	0.290	1	0.101	3
		S3	0.238	3	0.083	5
		S4	0.123	4	0.043	12
		S5	0.106	5	0.037	13

Table 8. Validation of the pairwise comparisons

Pairwise comparisons	*ξ*	*CI*	*CR*	*Threshold*	*Acceptable*
Eco-innovation dimensions	0.128	6.00	0.021	0.2848	Yes
Criteria under technological	0.150	7.37	0.020	0.2848	Yes
Criteria under institutional	0.121	6.00	0.020	0.2848	Yes
Criteria under organisational	0.117	6.00	0.019	0.2848	Yes
Criteria under social	0.106	6.00	0.018	0.3019	Yes

results for the four dimensions were within the acceptable range. Since the maximum upper value of aggregation $\tilde{a}_{BW}$ in fuzzy preferences was three, the consistency index $\tilde{\xi}$ can be computed using the equation $\tilde{\xi}^2 - \left(1 + 2 * \tilde{a}_{BW}\right) * \tilde{\xi} + \left(\tilde{a}_{BW}^2 - \tilde{a}_{BW}\right) = 0$. Consequently, the final CR for comparing the four dimensions was obtained as 0.0213, which is well below the threshold of 0.2848. This result indicates a high level of consistency in the first round of the group decision process and suggests that the weights assigned to the four dimensions were acceptable. Similarly, the pairwise comparison results of the criteria under each dimension were validated using the same method. The overall results are summarised in Table 8.

Discussion on the Cold Chain E-Fulfilment System

The results shown in Table 6 reveal the relative importance of each dimension and the prioritisation of the eco-innovation barriers in achieving eco-innovation practices based on the current cold chain e-fulfilment development status. This section analyses the results on the importance level of eco-innovation dimensions and the four main eco-innovation barriers, providing some feasible strategies.

Eco-Innovation Dimensions

Social eco-innovation is considered the most critical dimension for eco-innovation-oriented cold chain e-fulfilment as it involves all stakeholders' active participation and engagement in promoting sustainable practices. Mylan et al. (2015) emphasised that socio-cognitive coordination plays a critical role in the progress of eco-innovation, which goes beyond innovation to include social, institutional, and supply chain structures (Afshari et al., 2020; Ding et al., 2022). The e-commerce cold chain market should focus on stakeholders' behaviour, perceptions, and attitudes towards sustainability. Any eco-innovation practice in the cold chain e-fulfilment process may result in conflicting stakeholder behaviour. Therefore, the first step towards sustainable cold chain e-fulfilment is establishing shared meaning and visions related to eco-innovation, which can encourage multiple stakeholder involvement and enhance performance (Ogbeyemi et al., 2023).

Furthermore, social eco-innovation initiatives can encourage stakeholders to adopt more sustainable practices by increasing their knowledge and awareness of sustainability issues, promoting behaviour change, and fostering a culture of sustainability (Kar et al., 2019; Mirvis et al., 2016). This strategy was also highlighted by Afshari et al. (2020), who pointed out that even in developed countries with several established regulations and standards for environmental sustainability, there is still a need to familiarise stakeholders with the benefits of eco-innovative solutions. Moreover, as large retailers and non-profit organisations demonstrate a growing interest in promoting sustainable projects to support local communities and integrate sustainability into their core business operations (Risso, 2012), social eco-innovation can facilitate the development of new e-commerce cold chain business models and partnerships that improve operational efficiency and reduce environmental impact.

Technological eco-innovation is crucial in achieving sustainable cold chain e-fulfilment and is considered the second most important dimension. The global push to reduce the consumption of natural resources, particularly energy resources, and the use of toxic substances throughout the lifecycle of products and services have led to widespread support for green innovation in information technology (IT) (Faucheux & Nicolai, 2011). The IT sector plays a crucial role in promoting efficiency and sustainability in other sectors through dematerialisation, smart logistics, smart buildings, and smart grids (Janjua et al., 2023), which is particularly critical in the cold chain e-fulfilment industry. According to the research by Lee et al. (2014), eco-design was found to have a significant connection with technological innovation in achieving green supply chain development. Adopting up-to-date technology with eco-innovation can help companies achieve better environmental performance without compromising economic competitiveness, which is regarded as the most cost-effective pathway (Costantini et al., 2017; Liu et al., 2021). Additionally, developing and implementing advanced eco-innovation technologies can significantly improve the efficiency and effectiveness of cold chain operations, resulting in reduced energy consumption, lower costs, and better product quality and safety. For example, smart sensors, internet of things (IoT) devices, and data analytics can provide real-time monitoring and control of temperature and humidity levels, enabling quick detection and response to potential issues in the e-commerce cold chain.

Institutional eco-innovation is crucial for creating and enabling the environment for sustainable cold chain e-fulfilment, as progress towards sustainability may be slow or limited without it (Hofman et al., 2020). The eco-innovation literature widely recognises that well-designed policies and institutions, particularly those based on market instruments, are crucial in driving eco-innovation (Porter & Van Linde, 1995; Veugelers, 2012). Cold chain e-fulfilment faces increasing pressure to improve sustainability performance and adopt eco-innovative practices that reduce energy consumption, minimise carbon emissions, and enhance operational efficiency. This pressure is driven by changes in the regulatory environment, market forces, and evolving stakeholder expectations, including those of consumers, NGOs, local communities, and society (Ociepa-Kubicka & Pachura, 2017). Policies and regulations that encourage the adoption of sustainable technologies and practices, as well as the establishment of standards and certification schemes, can promote positive practices and improve accountability and transparency in cold chain e-fulfilment. Without the support of institutional eco-innovation, it becomes challenging to create a level playing field for all stakeholders, and there may be a lack of clarity regarding expectations and requirements for sustainable cold chain e-fulfilment.

Organisational eco-innovation involves adopting new and innovative processes, structures, and practices within an organisation to support sustainable and eco-friendly cold chain operations. It can significantly improve the efficiency and effectiveness of the cold chain e-fulfilment system by reducing the environmental impact, optimising resource usage, and enhancing overall performance. The commitment and support of senior management and cross-functional cooperation within the organisation for green supply chain management are crucial for successful eco-innovation practices (Lee et al., 2014). For example, implementing energy-efficient practices in warehouses and transportation can help reduce carbon emissions. Moreover, organisational eco-innovation can improve customer satisfaction (Loucanova et al., 2021). Organisations can enhance their brand management and build consumer loyalty by involving customers in the co-creation of sustainable solutions.

Eco-Innovation Barriers

This study identifies 'integration with legacy systems', 'high implementation costs', 'limited stakeholder engagement and communication', and 'limited awareness and education on eco-innovation' as the top four barriers to eco-innovation in the sustainability transition of cold chain e-fulfilment.

The study's findings highlight that 'integration with legacy systems' is a prominent barrier in the cold chain e-fulfilment sustainability transition. This barrier stems from existing legacy systems not being designed to accommodate the new eco-designed processes in cold chain e-fulfilment. According to Sajjad et al. (2015), implementing sustainable strategies often presents significant challenges to infrastructure, systems, and processes. In the e-commerce cold chain industry, practitioners have observed that while many players have begun addressing sustainability concerns, most are still in the early stages of the sustainability transition and encounter numerous barriers, particularly in system development. Historically, e-commerce platforms have prioritised delivery efficiency and product quality to quickly establish a market presence, focusing on competitive advantages such as variety, speed, quality, and affordability.

Practitioners emphasise that the rapid proliferation of hardware equipment and digital applications, along with eco-innovation in cold chain e-fulfilment processes, requires the development of infrastructure, software, and hardware that are compatible, applicable, universal, and standardised to achieve long-term SDGs instead of pursuing short-term gains. Additionally, some SMEs may face challenges in engaging in green and technological innovation activities within the cold chain e-fulfilment process due to lower technological capabilities and limited financial support compared to larger corporations. Moreover, participants highlight that introducing new technologies and practices that significantly change existing workflows and procedures is always challenging. There may be resistance to change among stakeholders accustomed to existing systems and processes. Companies can consider upgrading their legacy systems to newer, more advanced systems compatible with eco-innovation technologies to address this barrier. Also, middleware can bridge legacy systems and newer eco-innovation technologies, facilitating data transfer between systems without necessitating a complete overhaul of existing systems. Another viable solution is collaboration. By collaborating with eco-innovation technology providers, companies and technology providers can identify ways to integrate eco-innovation technologies with legacy systems cost-effectively and efficiently.

The second major barrier is 'high implementation costs'. Kiefer et al. (2018) emphasise that the availability of financial resources is a strong driver for organisations to develop eco-innovation practices. Revell and Blackburn (2007) argue that eco-costs are not incorporated into the price, leading to a barrier to sustainable development in industries. One of the most significant barriers to implementing eco-innovation in cold chain e-fulfilment is the fact that many wasteful and polluting goods, such as vegetables, fruits, and thermal packaging materials, are relatively inexpensive in monetary terms. At the same time, the technology investment required to reduce environmental risks, pollution, and resource utilisation is more expensive. Participants also note that the lack of standardisation in the cold chain industry leads to higher implementation costs due to the need for customisation and integration with existing systems. Potential solutions include the development of shared cold chain infrastructure and equipment leasing models to address this barrier, which can reduce companies' upfront investment costs. Collaboration between companies can also help standardise technologies and create economies of scale, lowering costs for all stakeholders. Governments and other organisations can create incentive mechanisms in three main categories, financial, ease of implementation, and recognition (Al Zaabi et al., 2013), such as tax credits or grants, to encourage SMEs to invest in eco-innovative technologies and equipment in the cold chain sector.

The barrier of 'limited stakeholder engagement and communication' is ranked third most prominent in cold chain e-fulfilment. Similarly, Marin et al. (2015) highlight that lacking engagement and communication in the supply chain hinders an organisation's ability to embrace sustainable practices. In cold chain e-fulfilment, stakeholders typically include product producers, logistics providers, retailers, policymakers, and consumers. Limited stakeholder engagement and communication may lead to a lack of buy-in from key stakeholders, resulting in resistance to change and difficulties in implementing new eco-innovation solutions (M. I. Khan et al., 2022; Rane et al., 2020). To overcome this barrier, effective communication and collaboration among these stakeholders are necessary to ensure that everyone is aligned with the sustainability goals and is willing to contribute to the success of eco-innovation in cold chain e-fulfilment. Fernandez-Vine et al. (2010) observed that some small companies comprehend the requirements of environmental regulations but fail to recognise the impact of external forces, such as customer demand for eco-friendly products and services. Therefore, all stakeholders involved in the cold chain e-fulfilment process need to communicate and collaborate to share information, coordinate activities, and resolve potential conflicts or issues that may arise during the fulfilment process. Regular communication channels like meetings, forums, and workshops can be established to enable stakeholders to share their opinions, views, and ideas. Furthermore, involving consumers in eco-innovation practices can help gain their support.

Another significant eco-innovation barrier in cold chain e-fulfilment is 'limited awareness and education on eco-innovation'. The knowledge required for developing eco-innovations differs from that needed for traditional innovation (De Marchi & Grandinetti, 2013). Therefore, stakeholders may not fully comprehend the benefits of adopting eco-innovation practices or the impact of their current practices on the environment (Kiefer et al., 2018). This lack of knowledge can lead to a lack of motivation to change and resistance to adopting sustainable practices in cold chain e-fulfilment. Thus, increasing awareness and education on eco-innovation is crucial to overcoming this barrier and promoting adopting sustainable practices in cold chain e-fulfilment. According to Cainelli et al. (2015), staff training and education can enhance or maintain the quality and quantity of available knowledge, directly influencing organisational eco-innovative outcomes.

Furthermore, raising stakeholders' awareness of environmental challenges can help gain their support and commitment to sustainable cold chain e-fulfilment. Active knowledge management can also lead to greater innovative performance (López-Nicolás & Meroño-Cerdán, 2011). In the context of an eco-innovation-oriented cold chain e-fulfilment system, where safety, quality, automation, digitalisation, and intelligence are highly demanded, the requirements for e-commerce cold chain practitioners tend to become higher. The participants in this study emphasised that a well-trained workforce could promote eco-innovation practices in cold chain e-fulfilment.

Practical Implications

The study's results highlight the importance of achieving eco-innovation consensus in the social dimension to ensure sustainable cold chain e-fulfilment. When industry actions align with stakeholders' values and expectations, it leads to better outcomes for the environment, economy, and society at large. Considering the diverse perspectives of stakeholders, such as consumers, regulators, policymakers, and environmental groups, is crucial, as cold chain e-fulfilment operates within a larger societal context. Social consensus-building on eco-innovation is essential for addressing potential conflicts and trade-offs between different sustainability objectives in cold chain e-fulfilment, such as reducing GHG emissions, minimising food waste, and ensuring food safety. By involving stakeholders in the eco-innovation process, it becomes possible to find common ground and develop solutions that benefit everyone.

In addition, identifying technological barriers through the STAF provides valuable insights for prioritising eco-innovation efforts in the cold chain e-fulfilment sector. Considering the potential concern regarding the high implementation costs in cold chain e-fulfilment, exploring feasible low-cost and low-carbon solutions in operating cold chain e-fulfilment helps mitigate this barrier. Karakuri Kaizen has gained increasing attention recently as a low-carbon and low-cost approach (Garza-Reyes et al., 2018). Karakuri is a concept that can be applied in various industry sectors. Tan et al. (2023) highlighted that Karakuri brings new ways to enhance labour productivity and implement environmentally friendly automation in service operations. The basic principle of Karakuri, which involves reducing overloads, waste, and irregularities in operations using simple mechanisms with little or no power, is universally applicable in the industry. Karakuri has been explored and developed in sectors such as production, warehousing, packaging, and order-picking systems in companies like Toyota Kirloskar Auto Parts India, Honda Motor Co., Ltd, and DENSO corporation, among others, to achieve automation with a focus on low costs and low carbon. Exploring the application possibilities of Karakuri in the links of the cold chain e-fulfilment process, such as packaging and order picking, may help mitigate the barrier of high implementation costs.

Overall, by prioritising the eco-innovation barriers in the cold chain e-fulfilment industry towards sustainability, this research helps stakeholders optimise their limited resources in addressing these barriers with a clear focus. Ultimately, this facilitates the industry’s growth in alignment with global SDGs. The study’s findings guide multiple stakeholders in the e-commerce cold chain sector, enabling them to make informed decisions and adopt eco-innovation practices that balance the rapid development of cold chain e-fulfilment with broader sustainability objectives.

CONCLUSIONS

This paper contributes to formulating a comprehensive framework for identifying and prioritising the eco-innovation barriers in cold chain e-fulfilment from a sustainability transition perspective. Seventeen eco-innovation barriers across four dimensions, namely technological, institutional, organisational, and social, are identified through the literature review and validated with expert inputs. Furthermore, these identified barriers have been prioritised using the GDM-FBWM to obtain their weights. The findings suggest that social and technological eco-innovation are seen as the top two dimensions in the current context of cold chain e-fulfilment from a sustainability transition perspective. Ensuring the sustainability of cold chain e-fulfilment requires various levels of cooperation and engagement among stakeholders within the same business network. Additionally, the global ranking of the 17 eco-innovation barriers indicates that integration with legacy systems, high implementation costs, limited stakeholder engagement and communication, and limited awareness and education on eco-innovation are the top four barriers that hinder the development of eco-innovation-oriented cold chain e-fulfilment. Based on these findings, corresponding strategies to overcome or mitigate these barriers have been proposed.

Although this study has made several significant contributions, some limitations allow further research. The results may be biased due to the experts' perspectives since the study was based on experts' opinions from academia and the related industry. Future research can focus on testing the effectiveness of the proposed framework in practice and exploring more comprehensive strategies to enhance sustainability in cold chain e-fulfilment systems.

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CONFLICTS OF INTEREST

We confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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