Sustainable Cold chain: Application of emerging technologies

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Abstract: India, being the world's second-largest producer of fruits and vegetables, paradoxically faces massive post-harvest losses. This wastage undermines challenges food safety and quality and sustainability goals. Recognizing these challenges, the government of India has prioritized cold chain development under numerous schemes with emphasis on infrastructure, quality assurance, green operations and integrated cold chain. Despite these initiatives, the cold chain network remains fragmented with inadequate technology adoption and collaboration between stakeholders. The need for robust cold chain systems is further accentuated by the rising consumer demand for frozen and processed foods and the increasing health and wellness concerns. This study highlights the pressing need for enhanced food safety, quality and technology-driven solutions to minimize wastage and improve sustainability. It presents sustainability indicators and the technologies that can help tackle these sustainability indicators. The study proposes a mixed method approach using both qualitative and quantitative analysis. The study will be of immense applicability to the policy and decision makers as they can prioritize investment related decision for an improved sustainable cold chain.

Keywords: Fruits and vegetables; cold chain; wastage, technology; sustainability.

Introduction

India, though being globally the second-largest producer of fruits and vegetables, faces a paradox of abundance and wastage. Nearly 25-50% of the produce is wasted along the farm-to-fork continuum thereby challenging the food security, farmer income and sustainability objectives [1]. Fast changing consumer preferences and evolving social structures have accelerated the demand for frozen and processed food products, hence reshaping the supply chain (SC) dynamics. Rising health and well-being concerns also have reinforced the necessity for food safety and quality.

Infrastructural components in the cold chain play a pivotal role in tackling these challenges, however its appropriate development and use in developing countries remains unsatisfactory. Lack of integration across SC links and inadequate adoption of latest technologies viz. Internet of Things (IoT), artificial intelligence (AI) and blockchain hamper efficiency and flexibility. This results in gaps in traceability, waste minimization and quality control.

Considering such challenges, Government of India gave emphasis to integrated CC development under initiatives such as Pradhan Mantri Kissan Sampada Yojana and many more. Many autonomous bodies such as NCCD (National Cold Centre for Development) were also set up to enhance value addition, food safety and green operations. As it is projected that Indian cold chain market will reach INR 5.06 trillion by 2028 at a CAGR of 18.25% [2], the segment presents enormous opportunities for transformation. Integration challenges, technology adoption and sustainability are critical to erecting an effective cold chain ecosystem. This will contribute towards food safety, reduction in wastage and ultimately meet evolving consumer needs.

Related work

Performance of a cold chain is exceedingly susceptible to temperature disruptions, poor monitoring and quality degradation [3-5]. Poor monitoring causes substantial food losses, particularly in case of perishable products. In order to gain competitive advantage, firms must innovate cold chain operations aligned with strategic plans [6]. Innovative cold chain model sustained by emerging technologies is vital to reduce waste and integrate information flows across stakeholders [7-8]. This also aligns with India's current challenge of fragmented cold chain infrastructure.

Technological advancements viz. wireless sensor networks and analytics can be employed to enhance traceability, reduce waste and improve quality in agri-food SCs [9-11]. Real-time data sharing across production, processing, warehousing and distribution ensures food safety and strengthens SC performance [12]. Knowledge availability across the CC partners enhances competitiveness [13]. Despite these findings, the role of information technology in achieving sustainability and competitive advantage in food SCs remains underexplored. Though the literature suggests that emerging technologies can bridge gaps in traceability and integration but adoption of technology in developing countries is still scarce. This underscores the need for research towards scalable, technology-driven cold chain models.

Sustainable supply chain management integrates economic, environmental and social dimensions while meeting stakeholder requirements as defined [14]. Sustainability remains a global challenge ranked among top ten unresolved concerns [15]. Cold storage, logistics and food processing pose nearly 2/3rd of hydrofluorocarbon emissions [16]. The IPCC [17] report suggests that responsible energy consumption and consumer awareness can limit global warming to below 2^{o}C. A 70% surge in agronomic production is projected by 2050, 50% of which can be achieved by slashing food wastage [18]. Sustainability research in cold chains is still nascent with insufficient emphasis on waste minimization and green practices [19][20]. Therefore, integrating sustainability into CC operations is crucial for reducing environmental impact while enhancing efficiency. The present study converges on three key insights as given below"

- Cold chain inefficiencies drive wastage and undermine competitiveness
- Emerging technologies offer solutions for traceability, integration and waste reduction but its adoption remains underutilized in developing countries
- Sustainability must be embedded into cold chain design to address emissions, food safety and long-term resilience

This paper highlights the need for technology-enabled and sustainability-driven cold chain models to minimize losses, ensure food safety and meet evolving consumer demands. The table below presents theme-wise few significant studies and key observations.

Table 1. Prior related studies

Theme	Author	Observations
Cold chain	Mustafa (2024); Qian (2022); Centobelli (2021); Bhatnagar(2019); Bremer(2018); Ali(2018); Singh & Shabani (2016)	• A firm's CC functioning is significantly affected by quality degradation and temperature breakdowns • 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
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 the entire agricultural SCs may be drastically affected by eco-friendly activities.
Emerging Technologies	Grover (2024); Veena (2024); Bhattacharyya (2021); Batwa & Norman (2020); Badia-Melis (2018);	• By sharing the real-time data from stages of processing, storage, and distribution traceability can be achieved with reliable information throughout SC, which would effectively assure 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

Key Contribution

The study provides valuable insights for the food cold chain, emerging technologies and sustainability. Inefficiencies such as temperature breakdowns and poor infrastructure directly impact SC performance. There is need for innovative cold chain that integrates information flows and reduces waste. Cold chain resilience is a critical enabler of food safety, quality and reduces losses. Information technology plays a significant role in enhancing traceability, real time monitoring and process quality. It also project that data sharing across stakeholders will improve efficiency, transparency and competitive advantage. The study also arrives at a research gap in linking technology adoption with sustainability outcomes. It is crucial that sustainability is embedded into cold chain practices to achieve long-term resilience and efficiency.

Method, Experiments and Results

From the literature review covered in the study, sustainability indicators have been identified across the three dimensions: economic, environmental and social. Figure 1 presents the proposed research framework.

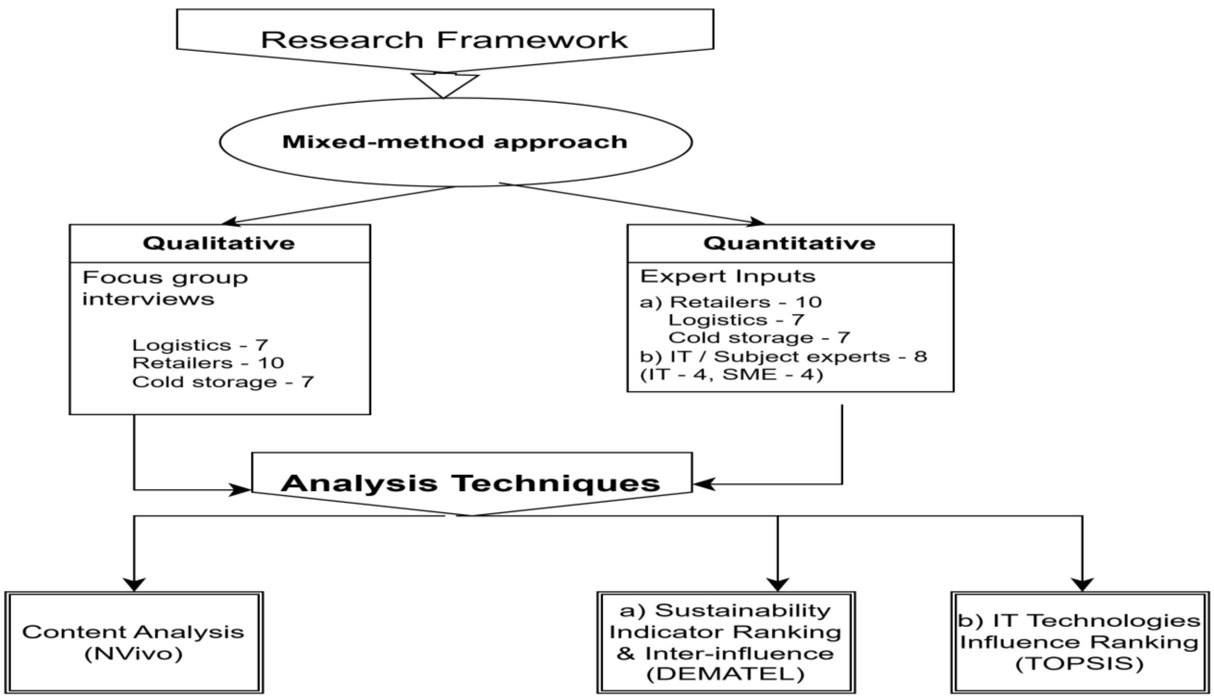

Figure 1. Research Framework

The study espouses a mixed-method approach to broadly assess cold chain management, sustainability indicators and role of emerging technologies. Two complementary instruments have been utilized for data collection: expert inputs and a questionnaire. Qualitative analysis is facilitated by a questionnaire with open-ended questions and captures stakeholder perspectives across CC operations. Responses gathered will be examined by employing NVivo to identify insights related to food safety, wastage minimization and sustainability practices.

To conduct quantitative analysis, expert inputs are collected from cold chain stakeholders, specifically logistics service providers, retailers, and cold storage service providers; and IT professional and subject matter experts. Sustainability indicators that were derived from the exhaustive literature review will be analyzed using DEMATEL (Decision Making Trial and Evaluation Laboratory), a multi criteria decision making method, also enabling identification of inter-influence amongst the indicators. Alongside, technologies such as IoT, AI, analytics and blockchain in enhancing these sustainability indicators will be examined using TOPSIS (Technique for Order Preference by Similarity to Ideal Solution**)**, another MCDM method. This dual analysis provides a robust framework to assess both stakeholder-driven sustainability priorities and technological enablers that can strengthen cold chain resilience, efficiency and sustainability outcomes. The sustainability indicators are presented in table 2.

Table 2. Sustainability Indicators

S.N.	Sustainability Dimension	Sustainability Indicator	Code
1	Eco sustainability	Efforts towards Cost reduction	CR
2	Eco sustainability	Effective use of Resources	RS
3	Eco sustainability	Real-time monitoring using IT	IT
4	Eco sustainability	Route Optimization	RO
5	Eco sustainability	Demand Prediction	DP
6	Env sustainability	Consideration of Product responsibility	PR
7	Env sustainability	Minimize Energy consumption	EC
8	Env sustainability	Control and reduce Carbon footprints	CF
9	Env sustainability	Use of Alternate sources of energy	AE
10	Env sustainability	Control Adverse environment impact	EI
11	Env sustainability	Use of Green CC practices	GP
12	Env sustainability	Compliance to Certification/ Standards	CS
13	Env sustainability	Use Organic production methods	OP
14	Social sustainability	Maintain Food attributes like Taste, Flavour, Weight, Nutrition, Shelf life & required environmental conditions	FA
15	Social sustainability	Traceability	TR
16	Social sustainability	Knowledge of quality parameters/ safety requirements/ environmental sustainability	KS
17	Social sustainability	Customer-centric in terms of response times	RT
18	Social sustainability	Availability of Information to all CC stakeholders	IN
19	Social sustainability	Training to all stakeholders	TR

The scope of this study is limited to identification of the sustainability indicators while the analysis will be presented in the consequent study.

Discussion

The study stresses upon cold chain management in India being at crucial juncture with inefficiencies in infrastructure and non-adoption of technology resulting in excessive levels of food wastage and adverse environmental impact. The research therefore tends to accentuate upon the interrelation between the identified sustainability indicators coupled with empowering role of emerging technologies. DEMATEL analysis will uncover the crucial sustainability enablers while TOPSIS will endorse significance of IOT, AI, analytics and blockchain in reinforcing these enablers. Together, such insights will certainly underline need for a cohesive, technology-enabled cold chain eco-systems that can help diminish losses, augment food safety while supporting the dynamic consumer preferences.

Contemplating further, various future directions emerge. Firstly, policy frameworks need to give precedence to technology adoption and integration across all the CC stakeholders. Secondly, collaboration amongst the stakeholders is elemental to form interoperable platforms enabling real-time data sharing leading to increased traceability and transparency. Thirdly, sustainability must be rooted into CC design, while emphasizing upon reduction in carbon emissions, promotion of scrupulous energy use aligned with global climate goals. Finally, futuristic research should be based on empirical studies on adoption of technology in developing markets.

By associating operational, technological and environmental aspects, this study furthers enhanced support for sustainable cold chain ecosystems. The insights into stakeholder insights through decision-making techniques offers a roadmap for policy and decision-makers and researchers to cooperatively transform India's cold chain sector into a crucial enabler of food safety and sustainability.

Policies should encourage technology adoption through incentives, subsidies and public private partnerships. Training programs initiatives are principal towards bridging the knowledge gap among stakeholders ensuring that even small-scale operators can capitalize using digital tools for monitoring, traceability and analytics. Also, seamless data sharing across SC players needs to be stressed upon. Firm norms should be enforced; awareness campaigns to be held and all efforts aligned with climate commitments can surely position cold chain sustainability for both food safety and climate resilience.

Conclusion

1. Problem statement addressed
    - Developing economies face grave challenges of huge wastage from farm to form in food supply chain.
    - Health concerns, rising consumer demand for convenience foods, and infrastructure existing more as silos will highlight the urgent need for integrating sustainability and technology.
    - The motivation stems from the need to minimize losses, ensure food safety and align with global sustainability goals.
2. Methodology used
    - A mixed-method approach combining qualitative and quantitative analysis.
    - Questionnaire with demographic and open-ended questions to be analysed through NVivio to portray stakeholder perspectives.
    - Through expert inputs, technology significance was evaluated using TOPSIS. This helped prioritize sustainability indicators using DEMATEL
    - A holistic view is obtained through the data collected from CC stakeholders, IT professionals and subject matter experts.
3. Key findings
    - A number of sustainability indicators viz. energy consumption, product responsibility, etc are codependent and critical drivers of sustainability.
    - Adoption of technological enhancement improves traceability and transparency.

- Use of systems can contribute towards reduction of wastage; enhancement of food safety while being aligned with environment goals and objectives.
- Industry collaboration and policy support are central to increase adoption and integration.

4. Limitations and Future Work
   - The study is limited by stakeholder perceptions and expert inputs
   - Geographic scope is restricted and findings may not generalize across diverse regions.
   - Future work can consider experimental studies to validate technology adoption models.
   - Research needs to also examine the cost-benefit analysis of emerging technologies, policy effectiveness and consumer-driver sustainability practices.

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