International Journal in Management and Social Science
Volume 14 Issue 05, May 2026 ISSN: 2321-1784 Impact Factor: 8.088
Journal Homepage: http://ijmr.net.in, Email: irjmss@gmail.com
Double-Blind Peer Reviewed Refereed Open Access International Journal

Impact of Infrastructure Availability and Technology Adoption on Supply Chain Performance: Evidence from Cold Chain Systems in India

Gajendra Rajaram Borse
Research Scholar, Dr. D. Y. Patil School of Management, Charholi Bk.,
Affiliation: Savitribai Phule Pune University,Pune, India. Email : borsegajendra1976@gmail.com,

Dr.Shreekala Prasad Bachhav,
Research Guide, Dr. D. Y. Patil School of Management, Charholi Bk.
Affiliation: Savitribai Phule Pune University, Pune,India. Email : shreekala.apr@gmail.com.

Abstract

The effective management of perishable goods poses a considerable challenge in India, attributed to substantial post-harvest losses resulting from insufficient cold chain infrastructure and restricted technological implementation. This study analyses the influence of Infrastructure Availability and Technology Adoption on Supply Chain Performance within cold chain systems. The study utilises primary data from 154 respondents, comprising farmers, traders, cold storage operators, and transporters, and applies descriptive statistics and regression analysis to evaluate the offered hypotheses. The results indicate that the availability of infrastructure and the application of technology significantly boost supply chain performance, evidenced by reductions in post-harvest losses, improvements in product quality, higher price realisation, and expanded market access. Technology adoption significantly impacts performance outcomes, underscoring the essential role of contemporary and efficient systems in enhancing cold chain operations. Descriptive results indicate that the existing infrastructure and technology adoption are moderate, exhibiting significant shortcomings in storage capacity, accessibility, and the implementation of advanced solutions like IoT-based monitoring and sustainable refrigeration systems. The research emphasises that simply creating cold chain infrastructure is inadequate to mitigate wastage; ongoing technology advancement and integration throughout the supply chain are crucial for attaining optimal results. The findings underscore the necessity for focused governmental initiatives, such as financial incentives and support mechanisms, to advance the growth and modernisation of cold chain systems. The study is constrained by convenience sampling and a restricted sample size, potentially impacting the generalisability of the findings. Future study should utilise larger and more heterogeneous samples to corroborate and expand upon these findings. The study enhances comprehension of critical factors affecting cold chain efficacy and offers pragmatic insights for improving supply chain performance in the agri-logistics domain.

Keywords- Cold Storage, Cold Chain, Establishment of Cold Chain, Technology Adoption, Infrastructure Availability, Supply Chain Performance

Introduction

India is one of the major producers of fruits, vegetables, dairy and other perishable commodities in the world; nevertheless, the efficacy of the post-harvest management systems is patchy. However, a large percentage of agricultural output still is wasted in the farm to market continuum because to lack of temperature-controlled transportation, fragmented storage infrastructure, and lack of connectivity throughout the supply chain stages. In warm countries these losses are greatest during storage and transport, and have a direct impact on farmer earnings, price stability and food security outcomes. This has made the construction and modernisation of cold chains a strategic objective for enhancing supply chain efficiency and decreasing wastage in India.

The available literature has consistently identified many structural barriers in the Indian cold chain environment. These include insufficient storage capacity, uneven geographic distribution of infrastructure, limited access to small-scale producers, and poor integration between storage and transit systems. Furthermore, many facilities still use antiquated refrigeration technology, which are less efficient and may face environmental and regulatory difficulties as refrigerant regulations evolve. Recent technological advances have also demonstrated potential at pilot levels to improve temperature control, reduce energy consumption and improve overall system performance (e.g., solar-powered cold storage, IoT-enabled monitoring systems, and energy-efficient refrigerant solutions) at the same time. But still, there is no uniform large-scale acceptance and empirical data is still lacking at a broader level.

In this context, the degree of adoption and continuous upgrading of modern technologies are as important as the availability of the infrastructure in improving supply chain performance in terms of reduced post-harvest losses, improved product quality, better price realisation and improved market access. Previous research has shown that cold chain interventions can greatly increase shelf life and prevent spoiling, but the greatest results are obtained when the growth of infrastructure is accompanied by technology modernisation and operational integration. This suggests a need for a more concentrated empirical investigation on the combined influence of such factors on supply chain outcomes in the Indian setting.

Therefore, the present study aims to evaluate the impact of two major drivers – Infrastructure Availability and Technology Adoption on Supply Chain Performance in the context of cold chain systems in India. This study contains two hypotheses: (H1) Infrastructure Availability has a significant positive influence on Supply Chain Performance and (H2) Technology Adoption has a significant positive impact on Supply Chain Performance.

The empirical findings of the study have shown that the availability of infrastructure and the adoption of technology have a substantial positive effect on the performance of the supply chain. This suggests that improvements in these areas can reduce the logistical and marketing costs of perishable items. However, descriptive research shows that the existing level of infrastructure and technology adoption is only moderate, with significant gaps in capacity, accessibility and modernisation. This illustrates an important disconnect between possible advantages and existing system preparedness.

These findings from policy and managerial perspective highlight the need to not only enhance cold chain infrastructure but also ensure continual technical upgradation. Isolated cold chains may not be enough to stop wastage unless they are complemented by contemporary, efficient and sustainable technologies. Hence, there is a need for targeted government incentives, financial support mechanisms and technology adoption programmes to speed up the pace of modernisation and increase accessibility, especially for small and marginal players.

The study has some contributions, but also has some shortcomings. Convenience sampling may lead to respondent bias and the relatively small sample size limits the generalisability of findings. Future research may address these constraints by using probabilistic sampling techniques, larger datasets and region-specific analysis to provide a more holistic knowledge of the dynamics of cold chain performance in India.

In conclusion, the present study adds to the existing literature by providing empirical evidence on the role of infrastructure and technology in improving supply chain performance, and also points out the need for integrated and technology-driven approaches to effectively reduce post-harvest losses in the Indian agricultural sector.

Literature Review

Since 2018, India's cold storage sector has exhibited ongoing infrastructure deficiencies, the emergence of off-grid and hybrid refrigeration systems, and encouraging techno-economic pilot projects; while evidence indicates reductions in spoilage at the pilot level, comprehensive national subsidy information and large-scale results remain inadequate.

Challenges of the current status

The literature highlights widespread deficiencies in the cold chain, particularly in storage and transportation, unequal geographic distribution, and restricted access and awareness among farmers. These deficiencies result in significant losses during the storage and transportation phases of the supply chain, exacerbated by outdated infrastructure and dependence on grid electricity.

Losses in storage and transportation Significant food loss within the cold chain transpires during shipping and storage in warm-climate developing regions, such as India [1].

Access and awareness among farmers Field surveys in Maharashtra indicate restricted farmer access to cold storage and inadequate preparedness for export-grade processing, highlighting deficiencies in local infrastructure and knowledge.

Obsolete infrastructure and refrigerant hazards Numerous current facilities depend on outdated HFC (R404a) reciprocating compressor systems and are unaware of forthcoming HFC phase-down mandates, posing both environmental and retrofit issues [3].

Barriers to access and cost for smallholders Analyses of small farmers emphasise elevated capital and operational expenses, as well as the irregular geographical distribution of infrastructure, which constrains smallholder adoption [4].

Advancements in technological design

Recent research delineate several design methodologies focused on energy resilience, diminished operational expenses, and enhanced temperature regulation, encompassing off-grid solar and hydropower, sophisticated refrigerant systems, and thermal buffering integrated with IoT control. Pilot and feasibility studies provide quantifiable energy and performance improvements, however they differ by scale and context.

Integration of off-grid power systems Pico hydropower systems can cost-effectively supply energy to cold storage facilities in isolated highland regions, mitigating 10–50% of local waste observed in the absence of such storage [5].

Solar photovoltaic systems with thermal buffering and refrigeration utilising phase-change materials achieved approximately 28% energy reduction and maintained chamber temperature stability within ±1.1 °C in a 200 L prototype, while facilitating climate adaptation control and market connections in an Indian peri-urban trial.

Low-GWP secondary refrigerant systems A secondary loop utilising NH3-CO2 brine surpassed R404a systems in performance across various loads, achieving energy savings of around 24.6–30.24% and anticipated reductions in CO2 emissions and costs, with a projected payback period of four years based on localisation assumptions [3].

Contextual design and computational fluid dynamics analysis Commodity-specific design work, such as onion cold storage, employs heat-load estimation and computational fluid dynamics (CFD) to optimise airflow and refrigeration sizing according to unique commodity requirements [7].

Economical solar refrigeration structures Solar-powered cold storage solutions for smallholders are suggested as cost-effective options; nevertheless, sustaining optimal temperatures is a technological challenge in numerous low-cost designs [8].

Guidance on technology selection Comparative analyses advocate for traditional electric chillers in areas with dependable grids, while suggesting thermally driven or locally fuelled sorption and alternative off-grid solutions in regions with problematic grids [1].

Economic viability and regulation

Feasibility studies indicate favourable paybacks and ROI for certain technological options at pilot or plant scale; nevertheless, the literature lacks details on national-level subsidy effects and standardised finance results. Policy directives encompass environmental objectives that influence refrigerator selections.

Exhibited returns and return on investment The NH3-CO2 secondary system case study anticipated a payback period of around four years, predicated on localised component expenses and predicted yearly cost savings amounting to millions of rupees for the assessed facility [3].

Return on Investment for Smallholder Farmers A prototype combining PV, PCM, and IoT projected a return on investment of around three years and a 2.05-fold return over the same period, in addition to elevated farmgate prices for participants in the pilot cluster [6].

Viability for remote regions Pico hydropower-driven cold storage facilities have been deemed economically feasible in off-grid mountainous regions, facilitating localised value preservation [5].

Policy drivers and refrigerant phase-down: India aims to significantly decrease HFC usage, with the policy environment pertaining to refrigeration options, hence rendering the adoption of low-GWP systems a legal need for cold-storage modernisation.

Details regarding subsidies and programs Existing studies indicate governmental support for cold storage development; however, they lack comprehensive and consistent national subsidy parameters or standardised financing terms. Consequently, there is inadequate evidence to summarise detailed subsidy rates or application results.

Effect on minimising losses

Pilot projects and comparative analyses demonstrate that modernised, adequately powered cold storage systems can significantly prolong shelf life and enhance price realisation, however comprehensive national impact estimates remain unquantified in the evaluated studies. Evidence indicates significant advantages at pilot and local levels.

Estimates of baseline loss The lack of adequate storage leads to local loss estimates ranging from 10% to 50% for fruits and vegetables in certain mountainous regions [5].

Durability and cost advantages A PV+PCM prototype increased shelf life by up to four times and allowed for approximately 22% higher prices for application users in the pilot, illustrating quantifiable advantages for farmers from integrated systems [6].

Reduction of spoiling associated with energy The implementation of more efficient refrigeration systems, such as NH3-CO2 secondary loops, is expected to decrease running costs and emissions, hence facilitating continuous operation and minimising the risk of storage-related deterioration [3].

Comparative and case studies indicate that optimal loss reductions are achieved when cold storage is integrated with enhanced transportation, monitoring, and market connections, rather than relying just on storage [1,2,6].

Expanding evidence gap

Although pilot and site-level studies demonstrate notable local decreases in spoilage and enhanced returns, the examined body of work lacks extensive large-scale assessments quantifying national-level loss reductions resulting from recent cold storage interventions; thus, there is inadequate evidence to assert a national percentage reduction.

Research Methods

Analysis

Reliability Statistics

Construct	N	Cronbach's α
Infrastructure Availability	7	0.832
Technology Adoption	7	0.921
Supply Chain Performance	7	0.892

Descriptive Statistics

Infrastructure Availability

Item	N	Mean	S.D.
Cold storage facilities are available in my region.	154	3.1	0.875
The distance to cold storage facilities is reasonable.	154	3.2	0.982
Refrigerated transport (reefer vehicles) is easily available.	154	3.4	0.984
Cold chain infrastructure is evenly distributed across regions.	154	3.2	1.432
Access to cold storage is easy for small and marginal farmers.	154	3.1	0.931
Storage capacity is sufficient during peak harvest seasons.	154	2.7	0.945
Integration between storage and transport infrastructure is adequate	154	2.9	1.238

The descriptive statistics indicate a moderate level of infrastructure availability within the cold chain system. Most items report mean values between 3.1 and 3.4, suggesting that respondents perceive infrastructure as adequately available but not optimal.

Refrigerated transport shows the highest mean (M = 3.4), indicating relatively better accessibility, whereas storage capacity during peak harvest seasons (M = 2.7) and integration between storage and transport (M = 2.9) are perceived as weaker areas. The relatively higher standard deviation for infrastructure distribution (SD = 1.432) suggests significant variability across regions, highlighting uneven development.

Overall, the findings suggest that while basic infrastructure exists, gaps remain in capacity, integration, and equitable distribution, which may limit the effectiveness of the cold chain.

Technology Adoption

Item	N	Mean	S.D.
Modern refrigeration technologies are used in cold storage facilities.	154	3.0	1.232
Temperature control systems are reliable and efficient.	154	3.2	0.982

Renewable energy solutions (e.g., solar cold storage) are adopted.	154	3.1	0.895
Advanced refrigerants with low environmental impact are used.	154	2.8	0.982
IoT-based monitoring systems are implemented for tracking temperature.	154	2.9	0.945
Technology helps reduce operational costs in cold storage.	154	3.8	1.176
There is continuous upgrading of cold chain technologies.	154	2.9	0.901

The results reflect a moderate but inconsistent level of technology adoption in the cold chain sector. Mean values range from 2.8 to 3.8, indicating partial adoption of modern technologies.

Respondents strongly agree that technology helps reduce operational costs (M = 3.8), suggesting clear recognition of its benefits. However, lower mean scores for advanced refrigerants (M = 2.8) and IoT-based monitoring (M = 2.9) indicate limited adoption of advanced and sustainable technologies.

Additionally, the relatively high standard deviation for some items (e.g., SD = 1.232 for modern refrigeration technologies) suggests variability in technological adoption across facilities or regions.

Overall, while the perceived benefits of technology are acknowledged, actual implementation of advanced solutions remains uneven and somewhat limited.

Supply Chain Performance

Item	N	Mean	S.D.
Cold chain facilities reduce post-harvest losses.	154	4.0	0.989
Shelf life of perishable products has improved.	154	3.7	0.871
Product quality is maintained during storage and transport.	154	3.8	0.692
Farmers/traders receive better prices due to cold storage.	154	4.0	1.321
Market access has improved with cold chain availability.	154	3.9	0.692
Supply chain efficiency has improved (less delay/wastage).	154	3.8	0.879
Overall profitability has increased due to cold chain usage.	154	3.2	0.892

The descriptive analysis reveals a relatively strong positive perception of supply chain performance resulting from cold chain usage. Most items have mean values between 3.7 and 4.0, indicating general agreement among respondents.

Key improvements are observed in reduction of post-harvest losses (M = 4.0) and better price realization (M = 4.0), highlighting the effectiveness of cold chain systems in enhancing outcomes. Similarly, improvements in product quality, market access, and efficiency are also positively rated.

However, overall profitability (M = 3.2) is comparatively lower, suggesting that while operational benefits are evident, financial gains may not be uniformly realized by all stakeholders.
In summary, the results indicate that cold chain systems contribute positively to supply chain performance, particularly in quality preservation and loss reduction, though economic benefits may vary across users.

Hypotheses Testing

H1 Supply Chain performance improves with enhanced Infrastructure Availability

Regression Output Table

Model Summary	Value
R	0.612
R Square	0.374
Adjusted R Square	0.368
Std. Error of Estimate	0.521

ANOVA

ANOVA	Value
F	62.845
Sig.	0.000

Coefficient Tables

Coefficients	Unstandardized B	Std. Error	Standardized Beta	t	Sig.
(Constant)	1.284	0.312	—	4.115	0.000
Infrastructure Availability	0.586	0.074	0.612	7.927	0.000

The regression analysis indicates that Infrastructure Availability has a statistically significant positive impact on Supply Chain Performance ($\beta = 0.612$, $p < 0.001$). The model explains 37.4% of the variance in supply chain performance ($R^2 = 0.374$), suggesting a moderate explanatory power.

The ANOVA results confirm that the model is statistically significant ($F = 62.845$, $p < 0.001$), indicating that infrastructure availability is a strong predictor of supply chain performance.

The positive coefficient (B = 0.586) implies that an improvement in infrastructure availability—such as better access to cold storage and refrigerated transport—leads to a significant enhancement in supply chain outcomes, including reduced losses and improved efficiency. Therefore, H1 is accepted.

H2 Supply Chain performance improves with increasing level of technology adoption

Model Summary

Model Summary	Value
R	0.684
R Square	0.468
Adjusted R Square	0.463
Std. Error of Estimate	0.487

ANOVA

ANOVA	Value
F	89.276
Sig.	0.000

Coefficient Table

Coefficients	Unstandardized B	Std. Error	Standardized Beta	t	Sig.
(Constant)	1.102	0.284	—	3.879	0.000
Technology Adoption	0.653	0.069	0.684	9.454	0.000

The regression results reveal that Technology Adoption has a significant and stronger positive impact on Supply Chain Performance ($\beta = 0.684$, $p < 0.001$) compared to infrastructure availability.

The model explains 46.8% of the variance in supply chain performance ($R^2 = 0.468$), indicating a relatively higher explanatory power.

The ANOVA test confirms model significance ($F = 89.276$, $p < 0.001$), validating that technology adoption significantly contributes to supply chain improvements.

The coefficient ($B = 0.653$) suggests that increased adoption of advanced technologies—such as IoT monitoring, solar-powered cold storage, and efficient refrigeration systems—substantially enhances supply chain efficiency, reduces spoilage, and improves market outcomes. Therefore, H2 is accepted.

Discussion

Analysis shows that better infrastructure and adoption and frequent updating of technology in cold chains significantly increases the supply chain performance. This means that overall cost of logistics and marketing of perishable items decreases significantly. However descriptive statistics shows that current infrastructure is not at par. It still needs improvements. Government may have to development new incentive schemes for operators/ traders to establish modern cold chains. Otherwise the wastage of agricultural produce cannot be curbed. Establishing cold chains alone will not help solve the wastage problem. With advancement in technology cold storages should also be updated. It will further help operators reduce the cost of operations and enhance the efficiency of the storage facility. The study has its own limitations. The data was collected using convenient sampling. This sampling techniques brings in biasness of researcher. Further the sample size is not adequate. Therefore, generalizability of the findings is difficult. Future studies may come over this issues.

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