Pharmaceutical Logistics Optimization: Addressing Cold Storage, Fuel Consumption and Inventory Imbalances - Evidence from a Regional Pharmaceutical Distributor

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DOI: https://doi.org/10.51244/IJRSI.2026.1309000218

Received: 03 October 2026; Accepted: 08 October 2026; Published: 21 October 2026

ABSTRACT

Pharmaceutical logistics is a critical operational function in the healthcare supply chain because medicine quality, distribution reliability and patient safety depend on cold-chain integrity, cost-efficient transportation and balanced inventory management. This study examines pharmaceutical logistics performance with reference to a WHO-GMP-certified regional pharmaceutical distributor in Coimbatore using survey evidence from 200 supply-chain stakeholders. In response to reviewer comments, the manuscript has been revised to make a clear distinction between survey-based evidence and operational performance records. The study uses descriptive analysis, one-way ANOVA with eta-squared, Kruskal-Wallis test, Mann-Whitney U test, Spearman rank correlation, Chi-square test with Cramer's V and exploratory composite performance indices. The analysis indicates that the major logistics concerns relate to temperature monitoring, inventory imbalance, fuel efficiency and technology adoption. Large-effect associations are observed between technology adoption and temperature control, and between logistics decision quality and inventory management. However, because longitudinal operational records such as temperature logs, fuel records, inventory turnover, expiry rates, stockout frequency and distribution cost data were not available, the results are interpreted as diagnostic and perception-based rather than causal or operationally audited evidence. The revised manuscript also proposes a measurable KPI framework for future operational validation, covering temperature compliance, storage utilization, fuel consumption per delivery, inventory turnover, stockout frequency, expiry rate, distribution cost and emergency delivery performance. The study recommends AI-enabled cold-chain monitoring, predictive inventory planning, route optimization and periodic KPI-based review as practical interventions for improving pharmaceutical logistics performance.

Keywords: Pharmaceutical Logistics; Cold-Chain Management; Fuel Efficiency; Inventory Management; Composite Indices; Cramer's V; Coimbatore; Pharmaceutical Distribution.

INTRODUCTION

Pharmaceutical logistics has become an important operational concern in the healthcare sector because pharmaceutical products must be stored, transported and distributed under conditions that preserve quality, safety and efficacy. Temperature-sensitive products such as vaccines, insulin, biologics and other cold-chain medicines require reliable storage and transportation practices. Ineffective logistics may lead to product wastage, stockouts, delayed delivery, higher fuel expenditure and reduced service reliability.

Regional pharmaceutical distributors operate under practical constraints such as fluctuating demand, road-dependent delivery networks, limited warehouse capacity, seasonal variations, emergency orders, supplier reliability issues and regulatory expectations. Therefore, logistics performance cannot be assessed only through a single indicator. Cold-chain reliability, fuel consumption, inventory balance, technology adoption, decision quality and distribution efficiency must be studied together.

The present study examines pharmaceutical logistics optimization with reference to a regional pharmaceutical distributor in Coimbatore. The study focuses on three operational problem areas: cold storage and temperature control, fuel consumption in transportation, and inventory imbalance.

The objectives of the revised study are:

- To evaluate stakeholder perceptions of current cold storage and temperature-control practices in pharmaceutical logistics.
- To assess perceived fuel-consumption and transportation-cost issues affecting pharmaceutical distribution.
- To examine inventory imbalance issues such as overstocking, understocking, stockout risk and expiry-related concerns.
- To apply suitable statistical tools, including non-parametric tests and effect-size measures, using the data available in the study.
- To propose a measurable operational KPI framework for future validation using temperature logs, inventory records, fuel records and distribution-cost data.
- To compare possible logistics optimization strategies such as cold-chain monitoring, route optimization, predictive inventory management and emergency-delivery planning.

REVIEW OF LITERATURE

The review is organized around AI-enabled pharmaceutical supply chains, cold-chain integrity, fuel efficiency, inventory synchronization, operational performance indicators and the resulting research gap.

2.1 AI and Sustainability in Pharmaceutical Supply Chains

Gupta, Ravi Kumar, and Khurana (2023) established that predictive analytics, adaptive routing, and intelligent inventory control can simultaneously minimize waste, fuel use, and emissions, positioning AI as a dual enabler of profitability and sustainability in supply chain management. Ojadi et al. (2024) confirmed through a PRISMA-based meta-analysis that coupling AI with big data analytics enhances sustainability through real-time monitoring, predictive maintenance, and optimized routing. Allam et al. (2025) demonstrated that Otto's AI-based forecasting reduced stock levels by 90 percent, illustrating how predictive systems can balance environmental and economic objectives. Saravanan, Chithirai Selvan, and Ajay (2025) documented that Indian logistics firms such as Delhivery, Shipsy, and Locus achieved faster delivery and reduced idle time after adopting AI-based route optimization. Khan and Khan (2025) further argued that AI strengthens supply-chain sustainability by improving demand visibility, reducing operational uncertainty and supporting faster managerial decision-making.

2.2 Cold-Chain Integrity and Digital Twin Technologies

Cold-chain integrity is central to pharmaceutical logistics because product safety and therapeutic effectiveness may be affected by temperature deviations during storage and transportation. Ali et al. (2025) found that integrating digital twins with AI and IoT technologies provides end-to-end visibility and predictive maintenance, resulting in reduced product loss and energy savings while supporting Good Distribution Practice compliance. Yusuf, Joseph, and Karuppannan (2025) demonstrated that AI-driven traceability and blockchain frameworks can reduce counterfeit risks and improve accountability in pharmaceutical supply chains. Rahi (2025) and Iqbal et al. (2025) confirmed that adaptive routing and predictive analytics can help preserve temperature stability throughout transport and storage. In the Indian context, Vishwakarma and Garg (2019) and Chandran (2020) established cold-chain logistics problems as among the major barriers to pharmaceutical supply-chain performance.

2.3 Fuel Efficiency and Green Transportation

Fuel consumption and route inefficiency are important cost drivers in pharmaceutical distribution, particularly where road transport dominates last-mile and regional delivery networks. Bharadwaj (2021) applied a deep-

reinforcement-learning framework that reduced route distance, fuel use and carbon emissions, thereby demonstrating the relevance of intelligent route optimization for sustainable logistics. Shawon et al. (2025) achieved comparable results using XGBoost and neural-network models for logistics optimization. Babatunde et al. (2025) emphasized that public–private partnerships are essential for scaling AI-based sustainable transport systems. Srivastava (2024) highlighted rising transportation costs as a major obstacle to India's pharmaceutical-sector growth, indicating that fuel-use optimization should be treated as both a cost-control and service-reliability issue.

2.4 Inventory Synchronization and Predictive Analytics

Inventory imbalance in pharmaceutical distribution occurs when overstocking, understocking, expiry loss and emergency procurement occur simultaneously. Ugwu et al. (2024) surveyed nearly 600 U.S. healthcare professionals and found that AI-based inventory systems reduced procurement errors, waste and administrative expenses, with a Random Forest model achieving strong predictive accuracy. Yerra (2025) demonstrated that AI-driven predictive analytics can reduce shipping delays. Goswami et al. (2025) reported substantial fuel savings and lower labour costs after AI-enabled supply-chain management was adopted across large organizations such as Walmart, Zara, DHL, Maersk and BMW. Chava and Saradhi (2024) further noted that generative AI and deep neural networks can support decision-making in modern pharmaceutical supply chains by improving forecasting, inventory visibility and operational responsiveness.

2.5 Operational Indicators, Regulation and Strategy Comparison

This research links the reviewed literature with operational indicators such as temperature-compliance rate, storage-utilization percentage, fuel consumption per delivery, delivery cost per route, inventory turnover, stockout frequency, expiry or damage rate, supplier on-time performance and emergency-delivery frequency. Shashi (2023) emphasized sustainable digitalization in pharmaceutical supply chains using the Theory of Constraints, supporting the need to identify and monitor system bottlenecks. Girish Gupta and Meenu Gupta (2025) proposed strategies for future-ready pharmaceutical supply chains, supporting integrated control-tower approaches rather than isolated interventions. These studies justify the revised manuscript's comparison of alternative strategies such as IoT-enabled cold-chain monitoring, AI-based demand forecasting, route optimization, FEFO/expiry dashboards, supplier scorecards and emergency-delivery protocols.

2.6 Research Gap

The reviewed literature establishes AI-enabled predictive analytics, digital twins, IoT monitoring, route optimization and inventory forecasting as important interventions for cold-chain integrity, fuel efficiency and inventory synchronization. However, many studies focus on large organizations, global cases or technology demonstrations, while regional Indian pharmaceutical-distribution settings remain less empirically examined. Further, prior studies often report individual statistical tests without integrating operational KPIs, practical effect sizes, longitudinal records or alternative strategy comparisons. The present study addresses this gap by providing survey-based diagnostic evidence from 200 pharmaceutical supply-chain stakeholders in Coimbatore and by adding an operational KPI framework for future validation using temperature logs, fuel records, inventory movement data, supplier-performance records and emergency-delivery data.

RESEARCH METHODOLOGY

3.1 Research Design and Setting

The study adopted a descriptive research design with reference to a WHO-GMP-certified pharmaceutical distributor headquartered in Coimbatore, Tamil Nadu. The sample consisted of 200 stakeholders across pharmaceutical supply-chain groups such as manufacturers, distributors, retail pharmacies, hospital/healthcare respondents and logistics providers. Convenience sampling was used. The structured questionnaire covered cold storage practices, transportation/fuel issues, inventory management, technology use and logistics decision-making.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue IX September 2026

The study is based on cross-sectional survey responses. Hence, the findings represent stakeholder perceptions and diagnostic relationships rather than audited operational performance records.

3.2 Statistical Tools and Analytical Rationale

The study used a multi-method statistical approach suitable for ordinal and categorical survey data. One-way ANOVA was used for group comparisons, while eta-squared was reported to understand practical magnitude. The Kruskal-Wallis test was added as a non-parametric robustness check. Mann-Whitney U test was applied to compare temperature reliability between technology adopters and non-adopters. Chi-square tests were supplemented with Cramer's V to interpret association strength. Spearman rank correlation was used to examine ordinal relationships. Composite indices were constructed as exploratory diagnostic indicators, not as validated operational audit scores.

3.3 Operational Indicator validation Framework

A measurable operational indicator validation framework is given below. These indicators should be collected in future research using historical and current operational records. In this present study, direct operational records were not available; therefore, the indicators are proposed as a validation framework.

Logistics Dimension	Recommended Measurable Indicator	Suggested Data Source	Use in Optimization
Cold-chain compliance	Percentage of shipments/storage hours within required temperature range	IoT sensors, data loggers, warehouse temperature logs	Identify temperature excursions and non-compliant storage points
Storage utilization	Average occupied cold-storage capacity (%)	Warehouse records, WMS data	Detect underutilized or overloaded storage capacity
Fuel efficiency	Fuel consumption per delivery / per kilometre	Vehicle logbooks, GPS, fuel bills	Compare route efficiency and vehicle performance
Inventory turnover	Cost of goods issued or sold / average inventory	ERP/WMS inventory records	Evaluate inventory movement efficiency
Stockout frequency	Number of stockout events per month / SKU	Sales and inventory records	Assess medicine availability and service reliability
Expiry rate	Expired stock value as percentage of inventory value	Batch records, expiry reports	Measure wastage and FEFO compliance
Distribution cost	Delivery cost per order / shipment / kilometre	Accounts and logistics records	Assess cost efficiency and route planning quality
Emergency deliveries	Number and cost of urgent deliveries	Dispatch records, order logs	Measure demand volatility and planning gaps
Supplier performance	On-time and complete delivery rate	Purchase and goods-receipt records	Assess supplier reliability and lead-time risk

Data Analysis and Interpretation

4.1 Demographic Profile

The sample consisted of 200 respondents. The respondent profile indicates representation from different age groups, experience levels and organization types across the pharmaceutical supply chain. Retail pharmacies and distributors represented a major share of the sample, followed by hospital/healthcare respondents, manufacturers and logistics providers.

Variable	Category	N (%)
Age	Below 20 years	8 (4.0)
Age	21-30 years	75 (37.5)
Age	31-40 years	45 (22.5)

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue IX September 2026

Age	41-50 years	50 (25.0)
Age	Above 50 years	22 (11.0)
Experience	Less than 1 year	37 (18.5)
Experience	1-3 years	37 (18.5)
Experience	4-6 years	74 (37.0)
Experience	Above 6 years	52 (26.0)
Organization Type	Manufacturer	31 (15.5)
Organization Type	Distributor	50 (25.0)
Organization Type	Retail Pharmacy	53 (26.5)
Organization Type	Hospital/Healthcare	41 (20.5)
Organization Type	Logistics Provider	25 (12.5)

ANOVA with Eta-Squared Effect Sizes

The ANOVA results indicate no statistically significant difference in cold storage reliability and inventory management perceptions across organization types. The effect-size values are negligible to small, indicating that logistics challenges are not concentrated in a single supply-chain node.

Variable	F	p-value	Eta-squared	Interpretation
Cold storage reliability	0.532	0.661	0.008	Non-significant; negligible effect
Inventory management	0.538	0.708	0.011	Non-significant; small/negligible effect

Kruskal-Wallis Non-Parametric Confirmation

Since the data are largely ordinal, the Kruskal-Wallis test was used as a non-parametric robustness check for inventory management performance across organization types. The test result, $H(4) = 4.782$, $p = 0.310$, confirms no statistically significant difference across groups. This strengthens the interpretation that inventory-related challenges are supply-chain-wide rather than limited to a single type of organization.

Test	Variable	Statistic	p-value	Decision
Kruskal-Wallis H	Organization type vs. inventory management	H(4)=4.782	0.310	No significant difference

Mann-Whitney U Test for Technology Adoption

A Mann-Whitney U test compared temperature reliability ratings between respondents using some form of monitoring technology and respondents reporting no monitoring system. The result indicates a statistically significant and practically large difference, supporting the recommendation for technology-enabled cold-chain monitoring. However, because the analysis is based on survey responses and not actual temperature logs, the finding should be interpreted as perceived reliability advantage rather than audited temperature compliance.

Comparison	n1	n2	U	p-value	Effect Size
Temperature reliability: monitoring technology vs. no system	164	36	4,529	<0.001	r = 0.53; large effect

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue IX September 2026

4.5 Chi-Square Tests with Cramer's V

Chi-square tests were supplemented with Cramer's V to assess practical magnitude. Technology type showed a large association with temperature control. Logistics decision quality showed a large association with inventory management performance. The temperature-control versus product-spoilage relationship was not significant and therefore should not be used to claim a practical association.

Association	Chi-square	df	p-value	Cramer's V	Interpretation
Temperature control vs. technology type	53.116	3	<0.001	0.515	Large association
Temperature control vs. product spoilage	64.20	3	0.903	Not computed	No significant association
Logistics decision quality vs. inventory management	86.244	4	<0.001	0.657	Large association

4.6 Spearman Rank Correlation Analysis

Spearman rank correlation results indicate that transport cost and temperature-control difficulties have small negative relationships with inventory performance. Cold-storage expansion and transport cost show a large positive relationship, suggesting that cold-chain expansion may increase logistics cost unless route planning and load consolidation are improved. Overstocking and understocking are strongly positively correlated, indicating forecasting and inventory-planning imbalance.

Variable Pair	Spearman rho	p-value	Interpretation
Transport cost vs. inventory management	-0.201	0.004	Small negative relationship
Temperature control vs. inventory management	-0.199	0.005	Small negative relationship
Cold storage facilities vs. transport cost	0.668	<0.001	Large positive relationship
Overstocking vs. understocking	0.689	<0.001	Large positive relationship

Exploratory Composite Performance Indices

Composite indices were constructed as exploratory diagnostic measures using available survey summaries. They should not be interpreted as validated operational KPIs because they are not derived from temperature logs, fuel bills, WMS records or ERP transaction data. They are useful as a preliminary framework for identifying which performance areas require priority attention.

Index	Basis	Score	Interpretation
Cold Chain Reliability Score (CCRS)	Availability of storage, perceived reliability and spoilage response	0.355	Critical gap
Inventory Stability Score	Inverse of overstocking and understocking instability	0.309	Critical gap
Fuel Efficiency Score (FES)	Fuel level, road-dependence and reactive logistics adjustment	0.328	Critical gap
Technology Adoption Index (TAI)	Weighted sophistication of monitoring technology	0.630	Approaching adequate
Pharmaceutical Logistics Performance Score (PLPS)	Weighted composite of all four indices	0.377	Critical gap

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue IX September 2026

Alternative Strategy Comparison

The table is intended as a managerial decision-support framework; actual selection should be based on cost-benefit analysis using operational data.

Strategy	Primary Problem Addressed	Data Needed for Implementation	Expected Benefit	Priority
IoT-enabled cold-chain monitoring	Temperature excursions and weak cold-chain visibility	Temperature logs, excursion alerts, storage capacity and product category	Improves temperature compliance and reduces spoilage risk	High
AI-based demand forecasting	Overstocking and understocking occurring together	Sales history, seasonal demand, stockout events, expiry dates and supplier lead time	Improves reorder planning and reduces inventory imbalance	High
Route optimization and delivery consolidation	Fuel consumption and road-dependent delivery cost	GPS routes, delivery frequency, fuel bills, vehicle load and distance	Reduces fuel cost and improves delivery efficiency	Medium to High
FEFO and expiry dashboard	Expiry loss and slow-moving stock	Batch-level expiry dates, SKU ageing and dispatch history	Reduces expiry-related wastage	High
Supplier-performance scorecard	Supplier unreliability and emergency procurement	Purchase order cycle time, fill rate and delay records	Improves procurement planning and supplier accountability	Medium
Emergency-delivery protocol	Urgent medicine availability and unplanned deliveries	Emergency order records, customer criticality and delivery time	Improves response time while controlling cost	Medium

FINDINGS, RECOMMENDATIONS AND CONCLUSION

5.1 Principal Findings

- The study identifies cold-chain reliability, fuel efficiency, inventory stability and technology adoption as key logistics performance areas requiring structured measurement.
- Technology adoption is strongly associated with perceived temperature-control effectiveness, indicating the importance of digital monitoring systems.
- Logistics decision quality has a large association with inventory management performance, suggesting that inventory imbalance is partly a decision-system problem.
- Overstocking and understocking co-occur, indicating poor demand forecasting and weak inventory synchronization.
- Organization type does not significantly explain logistics differences, implying that challenges are systemic across the supply chain.
- The composite PLPS is useful as an exploratory diagnostic score, but it should be validated using operational records before being used as an official performance benchmark.

Recommendations

- Implement IoT-enabled temperature monitoring with automatic alert mechanisms and periodic compliance reports.
- Collect and analyse historical temperature logs, fuel records, route data, inventory movement, expiry reports and stockout records.
- Introduce AI-supported demand forecasting using SKU-level sales history, seasonal patterns, supplier lead time and emergency order data.
- Use route optimization tools to reduce unnecessary travel distance, fuel consumption and delayed deliveries.
- Implement FEFO-based expiry dashboards and slow-moving stock alerts to reduce expiry-related wastage.

- Develop supplier scorecards covering delivery timeliness, order completeness, emergency response and quality compliance.
- Use PLPS as a quarterly diagnostic dashboard only after validating its components with operational data.

5.3 Limitations and Future Research

The study is limited by its single-regional-distributor context and the use of convenience sampling. The findings may not be generalized to all pharmaceutical distributors, regions or distribution models. The analysis is based mainly on cross-sectional survey responses; therefore, causal claims cannot be made. Longitudinal operational records such as temperature compliance logs, fuel consumption per route, inventory turnover, stockout frequency, expiry rates, supplier performance and distribution costs were not available. As a result, the optimization recommendations should be treated as evidence-informed managerial directions rather than as verified optimization outcomes.

Future research should integrate survey responses with ERP, WMS, GPS, IoT and accounting records. A stronger design would compare pre- and post-intervention performance after implementing digital cold-chain monitoring, predictive inventory planning or route optimization. Simulation modelling, inventory modelling and route analysis may also be used to compare alternative strategies under different demand and emergency-delivery scenarios.

CONCLUSION

This study provides diagnostic evidence on pharmaceutical logistics challenges relating to cold storage, fuel consumption and inventory imbalance in a regional pharmaceutical distribution context. The revised manuscript addresses the reviewer's concerns by distinguishing survey-based findings from operational evidence, adding measurable KPI indicators, incorporating effect-size interpretation and comparing alternative optimization strategies. The results suggest that technology-enabled monitoring and decision-support systems can improve logistics performance, but the effectiveness of such interventions must be validated through historical and current operational data. The study therefore contributes a practical framework for moving from perception-based diagnosis toward data-driven pharmaceutical logistics optimization.

Author Response to Reviewer Comments

Reviewer Issue	Action Taken in Revised Manuscript
Narrow focus on one regional distributor limits generalizability	The limitation has been explicitly stated; the manuscript now describes findings as regional and diagnostic, not universally generalizable.
Cold-chain compliance, fuel consumption and inventory imbalance require different indicators	A separate operational KPI framework has been added covering temperature compliance, storage utilization, fuel consumption per delivery, inventory turnover, stockouts, expiry rates and distribution costs.
Need historical and current operational data	The revised methodology clarifies that such records were not available and identifies them as necessary future validation data.
Optimization techniques such as inventory modelling, route analysis, forecasting or simulation may strengthen the study	The recommendations and future research sections now include demand forecasting, route optimization, inventory modelling and simulation as future extensions.
Need to consider regulatory requirements, demand variability, supplier performance and emergency deliveries	The KPI framework and strategy comparison now include supplier performance, emergency delivery monitoring, expiry control, FEFO and compliance-based cold-chain monitoring.
Compare alternative strategies	A new Alternative Strategy Comparison table has been added to guide managerial selection of interventions.

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