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Demand Uncertainty, Perishability and Disruption: A Systematic Literature Review of Inventory Decision Factors in Pharmaceutical Multi-Echelon Supply Chains

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Abstract

Pharmaceutical multi-echelon supply chains face considerable inventory-management challenges arising from demand uncertainty, product perishability, production-capacity limitations, and supply-chain disruptions. This study conducts a systematic literature review (SLR) to examine inventory-management techniques and to identify the critical factors influencing inventory optimization in pharmaceutical multi-echelon supply chains. Following the PRISMA protocol, eighteen peer-reviewed studies published between 2021 and 2026 and indexed in Scopus and ScienceDirect were selected. The review shows that demand stochasticity, forecast uncertainty, service-level requirements, and multi-echelon synchronization are the most frequently examined factors affecting inventory performance. Stochastic inventory optimization, multi-echelon inventory optimization, multi-objective optimization, and AI/DRL-based inventory optimization are the most widely used methods for improving inventory effectiveness, contributing to cost minimization, stockout reduction, and higher service levels. Nevertheless, research gaps remain in integrating shelf-life and expiration-risk considerations, production planning, sustainability, and disruption management within unified inventory-optimization frameworks.

Keywords: Pharmaceutical Supply Chain; Multi-Echelon Inventory; Inventory Management; Supply Chain Disruption

1. Introduction

Pharmaceutical industries operate among the most complex supply chains because of their critical role in ensuring the availability of healthcare goods and patient safety. A pharmaceutical supply chain typically comprises several interconnected stages, namely manufacturers, national distribution centers (NDCs), regional warehouses, distributors, healthcare providers, and consumers, whose efficiency determines medicine availability, continuity of medical services, and overall service quality. However, the growing complexity of multi-echelon systems poses a major obstacle to efficient supply-chain operations and inventory management [1].

Demand unpredictability is one of the main issues in pharmaceutical logistics. Demand is inherently random and shaped by disease incidence, epidemics, seasonality, government health policies, and institutional requirements [2], which makes accurate forecasting difficult. Forecast errors cause inventory imbalances across the chain. When demand exceeds the forecast, stockouts and unavailability occur and patients may be unable to obtain the medicines they need [3]. Conversely, when demand is overestimated, excess stock accumulates and increases holding, obsolescence, and disposal costs. These imbalances are particularly costly in pharmaceuticals, where most products, including medicines, vaccines, biologicals, and injectables, have limited shelf lives and require stringent, quality-controlled monitoring throughout their life cycle, which increases the likelihood of deterioration, expiry, and wastage together with high

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disposal fees [4]. Expired products must be handled in specific ways, which adds further complexity to inventory management [5].

Production-related factors also shape inventory decisions. Pharmaceutical firms rely largely on batch production characterized by long setup times, limited capacity, and regulatory constraints, which restrict flexibility in adjusting output to market demand [6] and create mismatches between planned production and actual demand [7]. A further significant problem in multi-echelon settings is the bullwhip effect, whereby small changes in customer demand are progressively amplified as information moves from health facilities and distributors to distribution centers and manufacturers [8]. Information distortion, which is driven by poor information sharing, fragmented decision-making, and inaccurate forecasts, produces schedule volatility, inefficient capacity utilization, excess safety stock, higher costs, and inventory misalignment across echelons [9]. In a multi-echelon pharmaceutical chain, this amplification can lead upstream manufacturers to plan production on the basis of demand signals that are far larger or more erratic than actual patient demand, which in turn affects batch sizing and capacity planning.

In addition, supply-chain disruptions caused by transport delays, supplier failures, geopolitical risks, regulatory changes, and public-health crises can severely affect inventory availability and service delivery. The impact is especially pronounced in multi-echelon supply chains, where interdependencies among players are high and a disturbance at one stage propagates quickly to the others. When such disruptions coincide with demand surges, the resulting shortages can compromise the continuity of medical services across the entire network.

The combined effect of demand uncertainty, perishability, manufacturing limitations, the bullwhip effect, and disruptions ultimately determines customer-service performance. Low stock levels mean that healthcare facilities cannot access medicines when they are needed, which negatively affects patient well-being and lowers satisfaction. Conversely, holding excess stock to avoid shortages increases operating costs and wastage, particularly for perishable products. Inventory management in this context is therefore a balancing act in which managers must weigh the cost of stockouts against the cost of overstocking and expiry.

Several strategies have been proposed to address these problems. A common approach is the continuous-review (Q, R) policy, in which the inventory position is monitored continuously and replenishment is triggered once it reaches a defined reorder point R, ordering a fixed quantity Q. Continuous-review policies tend to be more responsive to demand changes than periodic-review (T, S) policies and are therefore considered suitable for stochastic settings; however, their application in multi-echelon pharmaceutical supply chains remains challenging because reorder points and order quantities must be coordinated across several interdependent stages with different lead times and shelf-life constraints [10]. Given the rising complexity of pharmaceutical logistics and the growing importance of inventory optimization, a systematic review is warranted. Although prior research has explored demand forecasting, perishable-inventory management, production planning, supply-chain coordination, and risk reduction, the literature remains dispersed across diverse research streams, which makes it difficult to obtain an integrated picture of the field.

This study therefore conducts a systematic review of inventory-management methods in pharmaceutical multi-echelon supply chains, examining the operational factors that influence inventory decisions, namely stochastic demand, forecast uncertainty, epidemic effects, seasonality, shelf life, deterioration, expiry risk, batch processing, capacity limitations, setup times, multi-echelon structure, the bullwhip effect, and supply disruption, in order to identify the methods in use and the research gaps for improving pharmaceutical supply-chain performance. The research questions are:

- What inventory-management strategies have been proposed and applied in pharmaceutical multi-echelon supply chains?
- How do inventory-management factors influence inventory decisions in pharmaceutical supply chains?
- What research gaps and future directions can be identified from the existing literature?

2. Method

This research uses a systematic literature review (SLR) to identify, analyze, and synthesize scholarly work on inventory-policy optimization in multi-echelon supply-chain settings affected by probabilistic demand, batch production, and limited product lifetimes. The review follows an evidence-based methodology to ensure scientific validity and consistency [11], and proceeds through several phases: formulating research questions, searching the literature, selecting articles against predefined criteria, extracting data, and synthesizing results. Relevant literature was retrieved from two prominent scientific databases, Scopus and ScienceDirect. These databases were selected because they

provide a comprehensive index of peer-reviewed journals in supply-chain management, operations research, industrial engineering, and pharmaceutical logistics, and therefore offer broad and reliable coverage of the field under review.

The search was conducted between January and June 2026 using key terms relating to inventory management, pharmaceutical logistics, and multi-echelon systems, with the search string designed from the research objectives and preliminary searches: (“pharmaceutical supply chain” OR pharmaceutical logistics) AND (“multi-echelon” OR “multi-level supply chain”) AND (“inventory management” OR “inventory optimization” OR “inventory control”) AND (“stochastic demand” OR “demand uncertainty” OR seasonality OR epidemic) AND (“shelf life” OR perishability OR deterioration OR expiry risk OR “batch production” OR “capacity constraint” OR “setup time” OR “bullwhip effect” OR disruption).

2.1. The Criteria

Inclusion criteria were defined using a PICO logic. The population covers supply-chain systems, especially multi-echelon chains in pharmaceuticals, manufacturing, or perishable goods, where inventory coordination across echelons is important. The intervention concerns inventory-control methods such as the (Q, R) model and other continuous-review policies, the integration of probabilistic demand, batch-production inventory models, and perishability- or shelf-life-aware control. The comparison is made against alternative policies such as periodic-review systems or decentralized methods. Outcomes refer to inventory performance indicators such as service level, operating costs (total and holding cost), and waste reduction. Eligible publications were peer-reviewed articles and conference papers containing empirical research, modeling, or simulation, written in English, and published between 2021 and 2026.

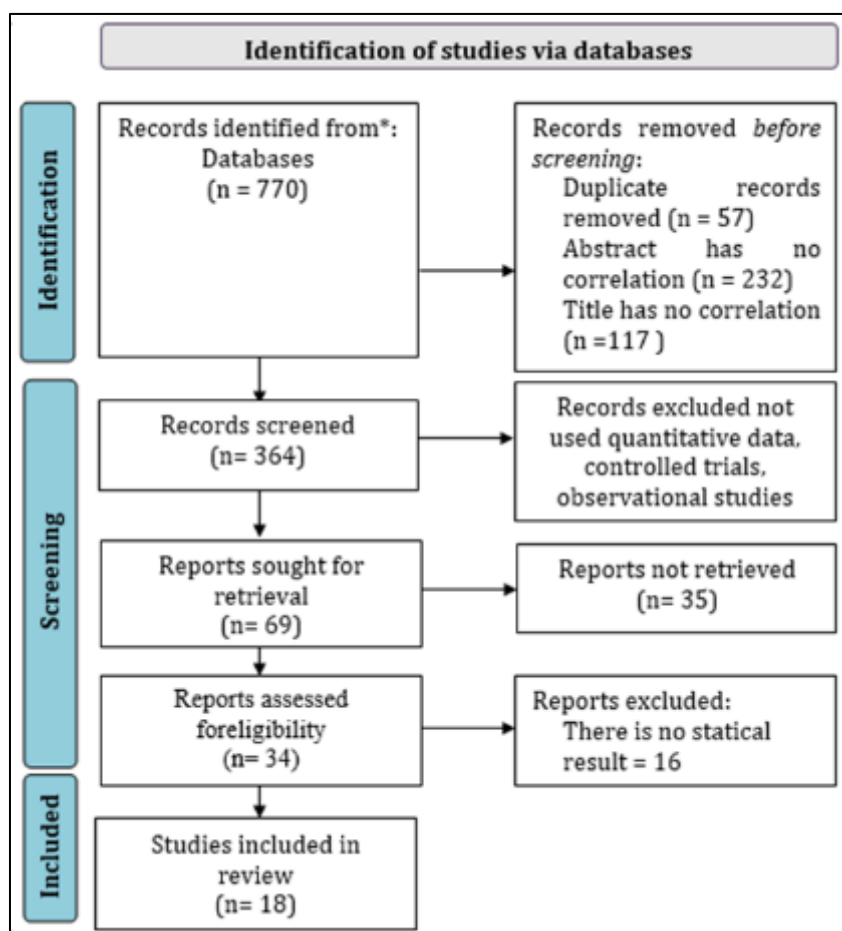


Figure 1 Literature Screening Results

Exclusion criteria were then applied to remove studies that were not relevant to the topic. With respect to population, studies that addressed only single-echelon inventory systems unrelated to multi-echelon settings were excluded. With respect to intervention, studies that did not employ any inventory-optimization technique, or that offered only qualitative discussion of inventory management, were excluded. With respect to comparison, studies that lacked a clear methodology or any basis for evaluating performance were removed, as were studies whose outcomes were unrelated

to cost, service level, or inventory efficiency. Finally, book chapters, editorial comments, and theses were excluded by publication type, together with non-English studies and those published before 2021.

2.2. Data Extraction

Data extraction was carried out systematically using a Microsoft Excel worksheet to organize and compare information from the selected studies [12]. The extracted fields included authors, publication year, research purpose, supply-chain structure (number of echelons), inventory model, demand nature (deterministic or probabilistic), production approach (batch or continuous), whether shelf life was considered, methodology (theoretical, experimental, or analytical), main findings, and the performance measures examined. Organizing the information in this way supported cross-study comparison, the identification of research trends, and the analysis of results across different methods. It also made it possible to detect which inventory-management factors and strategies were addressed most often and which received little attention, providing the basis for the gap analysis presented later in this review.

3. Results

This section summarizes the results of the systematic literature review on inventory-management approaches in pharmaceutical multi-echelon supply chains. In total, 18 studies published from 2021 to 2026 were selected for their relevance to inventory management and optimization in pharmaceutical settings. The selected studies cover a range of applications, including hospitals, pharmacies, pharmaceutical manufacturers, vaccine distribution, and broader multi-echelon healthcare supply chains. To answer the research questions, the findings are presented through five tables that, in turn, describe the characteristics of the studies, classify them according to inventory-management factors, classify the strategies used, report the frequency of each strategy, and map the research gaps with future directions.

Table 1 Characteristics of Selected Studies on Inventory Management in Pharmaceutical and Multi-Echelon Supply Chains (2021–2026)

No	Author(s)	Year	Industry Application /	Supply Chain Type	Methodology	Main Objective
1	Elarbi et al.	2021	Pharmaceutical drugs	Multi-echelon pharmaceutical supply chain	Stochastic multi-period mathematical model	Minimize inventory holding and shortage costs through collaborative inventory management
2	Ershadi and Ershadi	2022	Pharmaceutical logistics	Multi-period pharmaceutical network	Multi-objective optimization model	Optimize logistics planning and pharmaceutical distribution
3	Hansen et al.	2023	Pharmaceutical industry	Pharmaceutical supply chain	Case study and framework development	Identify key drivers influencing inventory-management decisions
4	Kochakkashani et al.	2023	Vaccines and pharmaceuticals	Four-echelon pharmaceutical supply chain	Mixed Integer Linear Programming (MILP)	Optimize pharmaceutical and vaccine planning under epidemic uncertainty
5	Sbai and Berrado	2023	Public pharmaceutical distribution	Multi-echelon distribution system	Simulation modeling	Evaluate and select appropriate inventory policies for distribution
6	Shen et al.	2024	Hospital drug supply chain	Hospital-supplier network	AI + Vendor Managed	Improve inventory accuracy and

					Inventory (VMI) case study	efficiency via AI-enabled management
7	Tajik et al.	2024	Multi-product manufacturing	Two-echelon supply chain	Mixed Integer Nonlinear Programming (MINLP)	Optimize production planning and inventory control
8	León et al.	2024	Multi-warehouse distribution	Multi-warehouse supply chain network	Stochastic inventory optimization model	Optimize service levels and order quantities under stochastic demand
9	Salas-Navarro et al.	2025	Pharmacy medicine supply	Pharmacy inventory system	Multi-product multi-period optimization model	Minimize medicine inventory costs while ensuring availability
10	Lu et al.	2025	Multi-echelon inventory systems	Multi-echelon supply chain	Deep Reinforcement Learning (PPO)	Optimize inventory policies under supply-chain disruptions
11	Kaur and Prakash	2025	Pharmaceutical inventory management	Retail pharmaceutical supply chain	Deep Reinforcement Learning (DRL)	Develop intelligent replenishment policies under dynamic demand
12	Wen et al.	2025	Pharmaceutical distribution channels	Multi-channel pharmaceutical supply chain	Game theory	Analyze pricing strategies and channel-competition impacts
13	Petridis et al.	2023	Manufacturing and distribution	Two-echelon supply chain	Entropy-based stochastic optimization	Assess operational risk and uncertainty in inventory decisions
14	Jagadeesan et al.	2025	Perishable inventory systems	Single-product supply chain	Stochastic inventory model with Markov chain	Analyze deterioration, waiting periods, and environmental uncertainty
15	Sugapriya et al.	2023	Medicine supply chain	Two-tier pharmaceutical supply chain	Multi-objective fuzzy programming	Optimize cost, quality, and delivery time simultaneously
16	Lotfi et al.	2023	Sustainable pharmaceutical supply chain	Closed-loop pharmaceutical network	Multi-objective optimization	Design sustainable pharmaceutical supply chains considering recycling
17	Deng et al.	2026	Hospital pharmaceutical inventory	SPD-based pharmaceutical supply chain	Robust optimization and CVaR model	Improve inventory resilience under supply and demand uncertainty
18	Mokhtari and Dehnavi	2026	Humanitarian pharmaceutical logistics	Sustainable pharmaceutical supply chain	Stochastic mixed-integer programming	Design sustainable, resilient supply chains using blockchain

Table 2 Validity Testing by SPSS

Author	Stochastic Demand	Forecast Uncertainty	Epidemic Effect	Shelf Life	Deterioration	Expiry Risk	Production Rate	Capacity Constraint	Multi-Echelon Structure	Service Level	Supply Disruption	Safety Stock	AI/DRL	VMI	Sustainability
Elarbi et al. (2021)	✓	✓							✓	✓					
Ershadi and Ershadi (2022)								✓	✓	✓					
Hansen et al. (2023)	✓	✓	✓	✓		✓		✓	✓	✓	✓				
Kochakkashani et al. (2023)	✓	✓	✓	✓		✓		✓	✓	✓					
Sbai and Berrado (2023)	✓								✓	✓		✓			
Shen et al. (2024)	✓	✓				✓			✓	✓			✓	✓	
Tajik et al. (2024)							✓	✓	✓						
León et al. (2024)	✓	✓							✓	✓		✓			
Salas-Navarro et al. (2025)	✓	✓		✓		✓		✓		✓					
Lu et al. (2025)	✓	✓							✓	✓	✓		✓		
Kaur and Prakash (2025)	✓	✓		✓		✓				✓			✓		
Wen et al. (2025)	✓								✓						
Petridis et al. (2023)	✓	✓					✓		✓		✓				

Jagadeesan et al. (2025)	✓			✓	✓	✓		✓							
Sugapriya et al. (2023)	✓	✓							✓	✓					
Lotfi et al. (2023)					✓	✓		✓	✓	✓					✓
Deng et al. (2026)	✓	✓						✓	✓	✓	✓				
Mokhtari and Dehnavi (2026)	✓	✓		✓	✓	✓		✓	✓	✓	✓				✓

Table 1 outlines the characteristics of the selected studies. Research on pharmaceutical inventory management in multi-echelon supply chains increased markedly from 2021 to 2026, reflecting growing interest in improving performance under uncertain and challenging conditions. Most studies address hospital operations, pharmacies, vaccine logistics, and healthcare logistics more broadly, and multi-echelon structures that link manufacturers, distributors, warehouses, hospitals, and pharmacies predominate. Methodologically, optimization approaches are most common, including stochastic programming, MILP, robust optimization, simulation, and artificial-intelligence methods. The main objectives are cost minimization, stockout mitigation, service-level improvement, uncertainty handling, and resilience. Recent studies pay increasing attention to innovative methodologies that involve artificial intelligence, deep reinforcement learning, blockchain technology, and vendor-managed inventory systems, which signals a gradual move from purely analytical models toward technology-enabled inventory management.

Table 2 categorizes the selected studies by the factors considered in inventory management. Stochastic demand is the dominant factor, underscoring the unpredictable nature of pharmaceutical demand and the importance of accurate forecasting and replenishment. Multi-echelon structure and service-level requirements are also prominent, highlighting the need for coordination among supply-chain partners to ensure medicine availability. Shelf life, deterioration, and expiry risk are important owing to product perishability, while capacity constraints, production rates, and supply disruptions appear in several studies. Recent work increasingly addresses technological factors such as artificial intelligence, deep reinforcement learning, and vendor-managed inventory, whereas sustainability, though emerging, remains comparatively uncommon.

Table 3 Classification of Inventory-Management Strategies in Pharmaceutical Multi-Echelon Supply Chains

Alt.	Inventory-Management Strategy	Supporting Studies	Description
A1	Stochastic Inventory Optimization	Elarbi et al. (2021); Petridis et al. (2023); León et al. (2024); Deng et al. (2026)	Determines optimal inventory policies from probability distributions of demand, cost, and supply variables.
A2	Perishable Inventory Management	Jagadeesan et al. (2025); Kochakkashani et al. (2023); Salas-Navarro et al. (2025)	Addresses perishable products where deterioration and expiry must be considered.
A3	Multi-Echelon Inventory Optimization	Elarbi et al. (2021); Sbai and Berrado (2023); Lu et al. (2025); Kochakkashani et al. (2023)	Coordinates inventory activities across the stages of the supply chain.
A4	Safety Stock Optimization	León et al. (2024); Sbai and Berrado (2023)	Determines optimal safety stock across supply-chain stages.
A5	Service-Level-Based Inventory Management	León et al. (2024); Salas-Navarro et al. (2025); Deng et al. (2026)	Sets inventory policies to target service levels, ensuring availability and minimizing stockouts.
A6	Vendor Managed Inventory (VMI)	Shen et al. (2024)	Shifts replenishment from hospitals/pharmacies to suppliers, improving coordination and efficiency.
A7	Artificial-Intelligence-Based Management	Shen et al. (2024); Kaur and Prakash (2025)	Applies AI to forecasting, replenishment planning, and decision-making.
A8	Deep Reinforcement Learning (DRL)	Lu et al. (2025); Kaur and Prakash (2025)	Uses learning algorithms that adapt replenishment to changing demand, inventory, and environment.
A9	Disruption-Resilient Inventory Management	Lu et al. (2025); Deng et al. (2026); Hansen et al. (2023)	Sustains service continuity under disruptions, pandemics, transport, or geopolitical events.
A10	Production-Inventory Coordination	Tajik et al. (2024); Petridis et al. (2023)	Synchronizes production planning with inventory storage and replenishment.
A11	Multi-Objective Inventory Optimization	Ershadi and Ershadi (2022); Sugapriya et al. (2023); Lotfi et al. (2023); Kochakkashani et al. (2023)	Considers multiple goals: cost, service, quality, flexibility, and sustainability.

A12	Collaborative Inventory Management	Elarbi et al. (2021); Shen et al. (2024)	Facilitates cooperation and information flow among supply-chain participants.
A13	Robust Inventory Optimization	Deng et al. (2026); Petridis et al. (2023)	Builds policies that withstand supply, demand, and operating-environment uncertainty.
A14	Simulation-Based Strategy Selection	Sbai and Berrado (2023)	Uses simulation to evaluate alternative inventory strategies.
A15	Sustainable Inventory Management	Lotfi et al. (2023); Mokhtari and Dehnavi (2026)	Incorporates environmental, economic, and social sustainability into design.
A16	Blockchain-Enabled Inventory Management	Mokhtari and Dehnavi (2026)	Increases transparency, coordination, and traceability via blockchain.

Table 3 classifies the inventory-management strategies in the reviewed studies. Stochastic, multi-echelon, and multi-objective optimization are the most common, used mainly to handle demand and supply uncertainty. Perishable-inventory management is also frequent because of medicine shelf life and storage requirements, while service-level-based management helps prevent shortages at healthcare organizations. Recent studies introduce AI and deep reinforcement learning, and collaboration approaches such as VMI and information sharing improve coordination. Robust and disruption-resilient techniques have become more prominent since the emergence of COVID-19, reflecting a growing need for inventory management that can cope with supply-chain disruptions. Taken together, these findings indicate that research on inventory management is shifting from conventional minimum-cost models toward intelligent, collaborative, and resilient frameworks.

Table 4 Frequency of Strategies Investigated in the Reviewed Literature

Strategy Category	Frequency
Multi-Echelon Inventory Optimization	4
Multi-Objective Inventory Optimization	4
Stochastic Inventory Optimization	4
AI/DRL-Based Inventory Management	4
Service-Level-Based Inventory Management	3
Perishable Inventory Management	3
Disruption-Resilient Inventory Management	3
Collaborative Inventory Management	2
Sustainable Inventory Management	2
Vendor Managed Inventory (VMI)	1
Blockchain-Enabled Inventory Management	1

Table 4 reports how often each strategy was investigated. Multi-echelon, multi-objective, and stochastic optimization, together with AI/DRL-based management, appear in four publications each, reflecting a focus on uncertainty handling, multi-level decision-making, and advanced technologies. Service-level-based, perishable, and disruption-resilient management appear in three studies each, confirming the importance of availability, expiry control, and disruption tolerance. Collaborative and sustainable management are less frequently studied, with two publications each, while vendor-managed inventory and blockchain-enabled management appear only once each. This distribution indicates that, although the field is broad, several promising strategies remain comparatively under-researched and offer clear opportunities for future work.

Table 5 Research-Gap Matrix on Inventory-Management Strategies

No	Research Theme	Existing Findings	Representative Studies	Identified Research Gap	Future Research Direction
1	Stochastic Inventory Optimization	Demand uncertainty and stochastic policies reduce costs and stockouts.	Elarbi et al. (2021); León et al. (2024); Petridis et al. (2023)	Limited integration of real-time demand data and dynamic adaptation.	Develop adaptive models using real-time healthcare and market data.
2	Multi-Echelon Inventory Management	Coordination across echelons improves overall performance.	Elarbi et al. (2021); Sbai and Berrado (2023); Lu et al. (2025)	Most models assume centralized coordination and full information.	Explore decentralized, collaborative decision-making in complex networks.
3	Perishable and Expiry-Sensitive Inventory	Shelf life and deterioration are increasingly modeled.	Jagadeesan et al. (2025); Kochakkashani et al. (2023); Salas-Navarro et al. (2025)	Few studies jointly consider shelf life, cold chain, and multi-echelon coordination.	Develop integrated models for temperature-sensitive products.
4	Service-Level Optimization	Service level balances cost and medicine availability.	León et al. (2024); Deng et al. (2026); Salas-Navarro et al. (2025)	Few studies use patient-centric metrics and healthcare outcomes.	Link inventory decisions to patient satisfaction and outcomes.
5	Supply-Chain Disruption Management	Disruptions from pandemics, logistics, and geopolitics are addressed.	Hansen et al. (2023); Lu et al. (2025); Deng et al. (2026)	Lack of comprehensive resilience frameworks linking risk, policy, and recovery.	Develop resilient systems with proactive and reactive strategies.
6	AI-Based Inventory Management	AI improves forecasting and replenishment decisions.	Shen et al. (2024); Kaur and Prakash (2025)	Empirical applications are limited and mostly single-organization.	Investigate large-scale AI implementation across networks.
7	Deep Reinforcement Learning (DRL)	DRL performs well under dynamic, uncertain conditions.	Lu et al. (2025); Kaur and Prakash (2025)	Rarely incorporates regulations, shelf life, and multi-objective concerns.	Integrate DRL with compliance, perishability, and sustainability.
8	Vendor Managed Inventory (VMI)	VMI improves visibility and replenishment efficiency.	Shen et al. (2024)	Very limited research in pharmaceutical multi-echelon settings.	Evaluate VMI across manufacturers, distributors, hospitals, pharmacies.
9	Robust / Risk-Based Optimization	Robust and CVaR approaches enhance resilience.	Petridis et al. (2023); Deng et al. (2026)	Focus on demand uncertainty, neglecting regulatory and supply risks.	Develop risk-sensitive frameworks covering multiple risk sources.
10	Sustainable Inventory Management	Sustainability is increasingly built into design.	Lotfi et al. (2023); Mokhtari and Dehnavi (2026)	Sustainability stays disconnected from daily inventory decisions.	Integrate environmental, social, and economic goals into control models.
11	Blockchain / Digital Technologies	Blockchain improves traceability and transparency.	Mokhtari and Dehnavi (2026)	Limited empirical validation and integration with optimization.	Explore blockchain-enabled real-time visibility and decision support.
12	Resilience During Epidemics	Epidemic-driven planning grew after COVID-19.	Kochakkashani et al. (2023); Hansen et al. (2023)	Emphasis on emergency response	Build resilience frameworks for future

				over long-term preparedness.	pandemics and emergencies.
13	Multi-Objective Optimization	Cost, quality, and service are optimized jointly.	Ershadi and Ershadi (2022); Sugapriya et al. (2023); Lotfi et al. (2023)	Social, environmental, and resilience objectives rarely combined.	Develop holistic models combining sustainability and resilience.
14	Data Integration and Information Sharing	Information sharing improves visibility and coordination.	Hansen et al. (2023); Shen et al. (2024)	Lack of interoperable systems among stakeholders.	Investigate platforms for end-to-end inventory visibility.
15	Humanitarian / Emergency Logistics	Disaster and humanitarian scenarios are emerging.	Mokhtari and Dehnavi (2026)	Strategies for humanitarian pharmaceutical chains underexplored.	Develop specialized policies for disaster-response operations.

Table 5 summarizes the key research gaps and future directions. Although inventory-management strategies have advanced considerably, important limitations remain. Most studies examine individual uncertainties or challenges, with few considering several jointly. AI and DRL show promise but are rarely applied in practice within pharmaceuticals, and sustainability is often neglected in inventory decisions despite its urgency. VMI and decentralized decision-making are seldom studied in multi-echelon pharmaceutical settings, and research integrating resilience, sustainability, blockchain, AI, and real-time information sharing is scarce. Finally, very few studies examine how the effectiveness of inventory management influences the quality of healthcare services delivered through these chains, which represents an important direction for future research.

4. Discussion

4.1. Inventory-Management Strategies Applied in Pharmaceutical Multi-Echelon Supply Chains

The review shows that diverse strategies are used to manage the growing complexity of pharmaceutical healthcare logistics. As Table 3 indicates, the most popular are stochastic inventory optimization, multi-echelon inventory optimization, multi-objective optimization, and AI/DRL-based management, mainly aimed at minimizing costs, avoiding stockouts, improving service levels, and increasing node-level efficiency. Multi-echelon optimization is especially relevant because pharmaceutical chains involve many players, namely manufacturers, distributors, warehouses, hospitals, and pharmacies, whose coordination reduces inventory without causing shortages [31]. Stochastic optimization is popular because deterministic methods cannot adequately capture supply uncertainty and demand variability, both of which are pronounced in pharmaceutical settings. By incorporating probability distributions of demand, cost, and supply, these methods determine inventory policies that better balance the risks of shortage and overstock

Recent studies show a clear move toward smart inventory management. AI and DRL, particularly proximal policy optimization (PPO), outperform traditional heuristic and rule-based policies [32], adjusting replenishment to dynamic changes in inventory levels, lead times, and demand. Collaboration-oriented strategies such as vendor-managed inventory, service-level improvement, and resilient management are also increasing [33]. Such smart systems adjust the replenishment process in line with dynamic changes in inventory levels, lead times, and other demand-related characteristics, which allows them to respond more quickly than static policies. These developments indicate that inventory management is increasingly treated as a strategic practice that strengthens supply-chain resilience, agility, and overall competitiveness in the pharmaceutical industry.

4.2. Influence of Inventory-Management Factors on Decision-Making

Table 2 shows that inventory management in pharmaceutical multi-echelon chains depends strongly on factors such as demand uncertainty, product characteristics, and production issues. Demand uncertainty is the most influential: stochastic demand and forecast uncertainty are the key parameters shaping replenishment, safety stock, and service levels. Demand fluctuations arise from changing patient needs, economic and environmental factors, seasonality, and unpredictable health crises. Because deterministic methods cannot capture this variability, stochastic optimization methods are widely applied in studies addressing this issue [34].

Product characteristics are also crucial. Unlike most goods, pharmaceuticals have limited shelf lives, deteriorate, and may expire, directly affecting ordering frequency, replenishment levels, storage, and turnover. Managers must balance medicine availability against expiry-related waste, finding the point where service level and cost intersect [25,35]. Production factors such as batch production, limited capacity, high setup costs, and long manufacturing lead times further influence replenishment and inventory placement, while supply-chain aspects such as disruptions, unreliable shipping, and multi-echelon structure add complexity. The literature therefore indicates that inventory decisions in pharmaceutical supply chains should account for several of these dimensions simultaneously rather than in isolation, because focusing on a single factor may improve one performance measure while worsening another.

4.3. Research Gaps and Future Research Directions

Despite considerable progress, the research-gap matrix highlights several gaps. First, although stochastic demand, multi-level organization, and service-level optimization are well covered, little work addresses the interaction among epidemic conditions, seasonality, batch processing, setups, and bullwhip-control techniques; most studies treat few factors at a time, reducing realism and applicability. The majority of studies consider only a few factors at a time, which makes the resulting models less realistic and less applicable to real operating conditions. Comprehensive models that simultaneously capture several of these factors are therefore needed if research is to support practical decision-making [36].

A second gap concerns integrating emerging technologies with pharmaceutical-specific requirements. Although AI, machine learning, and DRL are efficient, their practical application is limited and often ignores shelf life, regulatory compliance, cold-chain needs, and traceability [32]. Sustainable inventory management, blockchain-based visibility, and collaborative systems such as VMI also remain underused. Finally, there is tension between sophisticated, high-performing models and ease of implementation, since complex optimization or AI methods require substantial data and computation that can be costly, especially in developing countries. There is also an important tension between sophisticated, high-performing models and the simplicity required for implementation. Although complex optimization and artificial-intelligence algorithms can deliver better performance, they demand substantial data and computational resources, which can make adoption expensive, particularly for organizations in developing countries. Future research should therefore aim to develop inventory-management models that are robust and sustainable yet remain practical and implementable in real settings [33,37].

5. Conclusion and Recommendations

This systematic literature review analyzed 18 studies on inventory-management strategies in multi-echelon pharmaceutical supply chains from 2021 to 2026. Inventory management in this sector has grown more complex because of demand uncertainty, product perishability, manufacturing constraints, and supply-chain disruptions. Stochastic, multi-echelon, and multi-objective optimization, together with AI/DRL-based management, are the prevailing strategies, improving cost efficiency, reducing stockouts, raising service levels, and increasing operational flexibility across the network. Demand-related factors such as demand stochasticity and forecast uncertainty, product-related factors such as shelf life and perishability, and supply-chain factors such as disruptions and the multi-echelon structure of pharmaceutical supply chains are the main determinants of inventory decisions. These factors interact with one another, so that decisions taken at one echelon affect the performance of the others.

Several gaps remain. Future work should develop integrated strategies that jointly address demand uncertainty, perishability, production scheduling, disruption management, and sustainability. More attention is needed to modern technologies such as blockchain, digital twins, and AI to enhance visibility and traceability, and to empirical validation of advanced models in real pharmaceutical supply chains, especially in developing countries. In addition, more empirical studies are needed to validate advanced optimization and artificial-intelligence models within real pharmaceutical supply chains, since much of the current evidence is based on simulation or single-organization cases. Overall, the field would benefit from more practical and implementable inventory-management solutions that are tailored to the specific characteristics of pharmaceutical products and to the operating conditions of multi-echelon supply chains, including those in developing countries

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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