TJPP วารสารเภสัชกรรมไทย ปีที่ 18 เล่มที่ 2 เม.ย.-มิ.ย. 2569

PSU PRINCE OF SONGKLA UNIVERSITY

Research article

Analysis of Inventory Management Strategies and System-Level Models for Mitigating Drug Shortages in Narcotic and Psychotropic Substance Supply Chains : A Scoping Review with Health Policy Implications

Sanchai Chanto[1], Cha-oncin Sooksriwong[1], Thananya Wasusri[2]

[1]Doctor of Philosophy Program in Pharmaceutical and Health Sciences, Faculty of Pharmacy, Thammasat University

[2]Department of Industrial Engineering, Faculty of Engineering, Mahidol University

Abstract

Objective: To identify and synthesize inventory management strategies and modeling approaches for mitigating drug shortages, and to determine appropriate models for understanding, simulating, and analyzing drug shortages in narcotic and psychotropic substance (NPS) supply chain as a complex system. **Methods:** A structured search was performed following Arksey and O'Malley's five-stage framework and the PRISMA-ScR guidelines across four electronic databases including PubMed, Web of Science, ScienceDirect, and IEEE Xplore. The articles published during 2000 and 2024 were retrieved. The inclusion criteria covered peer-reviewed studies in English that focused on strategies, models, or technologies for managing drug shortages. Out of 4,202 records, 29 studies met the eligibility criteria for detailed analysis. **Results:** The scoping review identified four major thematic clusters in 29 studies for drug shortages in pharmaceutical supply chains. The largest thematic cluster was digital transformation and technology adoption. The most commonly reported cluster was identified in 17 studies (58.6%), followed by management strategies and optimization in 8 studies (27.6%). System analysis and modeling approaches were identified in 7 studies (24.1%), while policy, governance, and risk management appeared in 6 studies (20.7%). Traditional inventory management techniques, such as safety stock policies and ABC-based analyses, were commonly applied but demonstrated limitations when used in isolation within highly regulated contexts. Digital technologies primarily function as enabling tools, improving visibility and coordination. In the literature, system dynamics modeling has been recognized as particularly suited for analyzing feedback-dependent and delayed regulatory systems, while optimization or visibility-enhancing technologies usually work with fixed policy parameters. These are all significant components of highly regulated NPS supply chains. **Conclusions:** The study characterizes drug shortages in NPS supply chains as complex regulatory system challenges rather than merely logistical issues and approaches modeling methodologies through a perspective of system complexity. The study also highlights methodological, policy, and contextual factors specific to NPS systems in developing countries. Integrating inventory management with regulatory systems analysis establishes a foundation for more comprehensive, policy-oriented modeling frameworks.

Keywords: drug shortage, supply chain management, system dynamics, narcotic and psychotropic substances, inventory optimization

Received: Jan 16, 2026, **Revised manuscript received:** Feb 18, 2026, **Accepted:** Feb 23, 2026

Correspondence: Cha-oncin Sooksriwong, Faculty of Pharmacy, Thammasat University (Rangsit Campus), Khlong Nueng, Khlong Luang District, Pathumthani 12120 **E-mail:** chaoncin@tu.ac.th

PSU PRINCE OF SONGKLA UNIVERSITY

บทความวิจัย

การวิเคราะห์กลยุทธ์การบริหารเวชภัณฑ์คงคลังและแบบจำลองเชิงระบบเพื่อลดปัญหาการขาดแคลนวัตถุเสพติดในห่วงโซ่อุปทาน: การทบทวนวรรณกรรมอย่างมีขอบเขตเชิงนโยบาย

สัญชัย จันทร์โต[1], ชะอรสิน สุขศรีวงศ์[1], ธนัญญา วสุศรี[2]

[1]หลักสูตรปรัชญาดุษฎีบัณฑิต สาขาวิชาวิทยาศาสตร์เภสัชกรรมและสุขภาพ คณะเภสัชศาสตร์ มหาวิทยาลัยธรรมศาสตร์
[2]ภาควิชาวิศวกรรมอุตสาหการ คณะวิศวกรรมศาสตร์ มหาวิทยาลัยมหิดล

บทคัดย่อ

วัตถุประสงค์: เพื่อค้นหาและสังเคราะห์กลยุทธ์การจัดการสินค้าคงคลัง รวมถึงแนวทางการสร้างแบบจำลองที่ใช้ในการแก้ไขปัญหาการขาดแคลนยา และเพื่อระบุแบบจำลองที่เหมาะสมสำหรับการทำความเข้าใจ การจำลอง และการวิเคราะห์ปัญหาการขาดแคลนยาในห่วงโซ่อุปทานของยาเสพติดให้โทษและวัตถุออกฤทธิ์ต่อจิตและประสาทในฐานะของระบบที่ซับซ้อน **วิธีการ:** การศึกษาใช้การสืบค้นแบบมีโครงสร้างเพื่อค้นหาวรรณกรรมตามกรอบแนวคิด 5 ขั้นตอนของ Arksey and O'Malley ร่วมกับแนวทาง PRISMA-ScR โดยใช้ 4 ฐานข้อมูล ได้แก่ PubMed, Web of Science, ScienceDirect และ IEEE Xplore การวิจัยค้นหาบทความที่ตีพิมพ์ระหว่างปี พ.ศ. 2543 ถึง 2567 เกณฑ์คัดเลือกบทความ คือ งานวิจัยที่ผ่านการประเมินโดยผู้ทรงคุณวุฒิที่ตีพิมพ์เป็นภาษาอังกฤษ ซึ่งมีเนื้อหาเน้นกลยุทธ์ แบบจำลอง หรือเทคโนโลยีสำหรับการจัดการปัญหาการขาดแคลนยา จากบทความทั้งหมด 4,202 รายการ มีงานวิจัย 29 เรื่องที่เข้าเกณฑ์และถูกนำมาวิเคราะห์โดยละเอียด **ผลการวิจัย:** การทบทวนแบบกำหนดขอบเขตพบประเด็นหลัก 4 กลุ่มจากงานวิจัย 29 เรื่องเกี่ยวกับการขาดแคลนยาในห่วงโซ่อุปทานยา กลุ่มที่มีสัดส่วนมากที่สุด คือ การเปลี่ยนผ่านสู่ดิจิทัลและการนำเทคโนโลยีมาใช้โดยพบใน 17 เรื่อง (ร้อยละ 58.6%) รองลงมา คือ กลยุทธ์การจัดการและการหาค่าเหมาะที่สุดเพื่อเพิ่มประสิทธิภาพ 8 เรื่อง (ร้อยละ 27.6) การวิเคราะห์ระบบและการสร้างแบบจำลองพบใน 7 เรื่อง (ร้อยละ 24.1) และด้านนโยบาย การกำกับดูแล และการบริหารความเสี่ยงพบใน 6 เรื่อง (ร้อยละ 20.7) วิธีการจัดการสินค้าคงคลังแบบดั้งเดิม เช่น นโยบายสต็อกกันชน (safety stock) และการวิเคราะห์แบบ ABC ถูกนำมาใช้บ่อย แต่มีข้อจำกัดเมื่อใช้ลำพังเพียงวิธีเดียวในบริบทที่มีการควบคุมที่เข้มงวด เทคโนโลยีดิจิทัลส่วนใหญ่ทำหน้าที่เป็นเครื่องมือสนับสนุน ช่วยเพิ่มการมองเห็นข้อมูลและเพิ่มการประสานงาน ในวรรณกรรมพบว่าแบบจำลอง system dynamics เหมาะอย่างยิ่งสำหรับการวิเคราะห์ระบบกำกับดูแลที่มีวงจรป้อนกลับ (feedback) และมีความล่าช้า (delay) ขณะที่เทคโนโลยีด้านการเพิ่มประสิทธิภาพหรือเพิ่มการมองเห็นข้อมูล มักได้ผลดีภายใต้พารามิเตอร์นโยบายที่กำหนดตายตัว ซึ่งทั้งหมดเป็นองค์ประกอบสำคัญของห่วงโซ่อุปทานของยาเสพติดให้โทษและวัตถุออกฤทธิ์ต่อจิตและประสาทที่ถูกกำกับอย่างเข้มงวด **สรุป:** การศึกษานี้ชี้ให้เห็นว่าปัญหาการขาดแคลนยาในห่วงโซ่อุปทานของยาเสพติดและวัตถุออกฤทธิ์ต่อจิตและประสาท คือ ปัญหาในระบบกำกับดูแลที่มีความซับซ้อนมากกว่าเป็นปัญหาด้านโลจิสติกส์เพียงอย่างเดียว และเสนอให้พิจารณาแนวทางการสร้างแบบจำลองภายใต้มุมมองของความซับซ้อนในระบบ นอกจากนี้ยังชี้ให้เห็นปัจจัยด้านระเบียบวิธี นโยบาย และบริบทที่เฉพาะเจาะจงต่อระบบยาเสพติดให้โทษและวัตถุออกฤทธิ์ต่อจิตและประสาทในประเทศกำลังพัฒนา การบูรณาการการบริหารสินค้าคงคลังเข้ากับการวิเคราะห์ระบบกำกับดูแลจะช่วยวางรากฐานสำหรับการสร้างแบบจำลองที่ครอบคลุมยิ่งขึ้นและมุ่งเน้นเชิงนโยบายมากขึ้น

คำสำคัญ: ยาขาดแคลน การจัดการห่วงโซ่อุปทาน พลวัตเชิงระบบ ยาเสพติดและวัตถุที่ออกฤทธิ์ต่อจิตประสาท การเพิ่มประสิทธิภาพสินค้าคงคลัง

Introduction

Drug shortages have become a persistent and increasing problem in pharmaceutical supply chains (PSCs) worldwide, impacting healthcare systems in both high and low-income countries (1). Shortages of essential medicines disrupt clinical services, compromise patient safety, and increase healthcare costs through treatment delays and the use of alternative therapies (2). The severity of this issue has increased in recent years due to the globalization of pharmaceutical manufacturing, supply chain disruptions, and a growing dependence on a few manufacturers. On the supply side, manufacturing disruptions, limited production capacity, quality issues, and dependence on a few or geographically concentrated suppliers can restrict availability (1-3). On the demand side, demand uncertainty, sudden surges in clinical needs, and poor forecasting contribute to mismatches between supply and consumption. Regulatory factors further complicate this situation, as approval processes, licensing requirements, import controls, and compliance obligations often cause delays and reduce system flexibility. Importantly, these factors interact over time, creating feedback effects and delays that increase the risk of shortages (3).

The supply chains of narcotic and psychotropic substances (NPS) face additional challenges beyond those encountered in conventional pharmaceutical products (4,5). NPS medicines are governed by strict international conventions and national regulations designed to prevent misuse, diversion, and illegal distribution. These controls often involve quota systems, multi-level approval processes, and oversight by multiple regulatory agencies (4,5). While such measures improve security, they also add to administrative complexity, extend lead times, and reduce the ability to respond quickly to demand fluctuations or supply disruptions. As a result, even small disturbances in the NPS supply chain can spread throughout the system and cause prolonged drug shortages, highlighting the inherently complex and interconnected nature of this system (3).

Many studies have examined drug shortages and suggested strategies to manage inventory. Existing approaches remain fragmented and often focus on isolated operational components. In NPS supply chains, these limitations are more pronounced because generic inventory models rarely account for strict quota controls, licensing constraints, and regulatory-induced delays. Traditional methods such as safety stock and reorder point models assume relatively stable conditions, therefore excluding the dynamic interactions between regulation, demand variability, and supply constraints. Digital technologies enhance the visibility of supply chain issues, but they don't fix structural regulatory problems (4-7). This gap shows that we need integrated, system-level frameworks for addressing drug shortages in highly regulated NPS situations. Consequently, this scoping review was conducted to examine drug shortages not merely as logistical inefficiencies, but as emergent consequences of interrelated operational, behavioral, and regulatory mechanisms. Static regulatory tools, like annual quota allocations and licensing controls, interact dynamically with hospital stockpiling behavior, supplier lead times, and changing demand in NPS systems. Feedback loops, delays, and the effects of policy resistance result from these interactions. The conceptual basis for implementing dynamic modeling rather than relying solely on linear optimization techniques is provided by addressing drug shortages through a complexity lens. This study aims to identify and synthesize inventory management strategies and models used to mitigate drug shortages in the NPS supply chain, and to propose a suitable modeling approach to develop policy recommendations for Thailand's NPS supply chain.

Conceptual framework

The study is secondary research to review inventory management strategies and modeling on drug

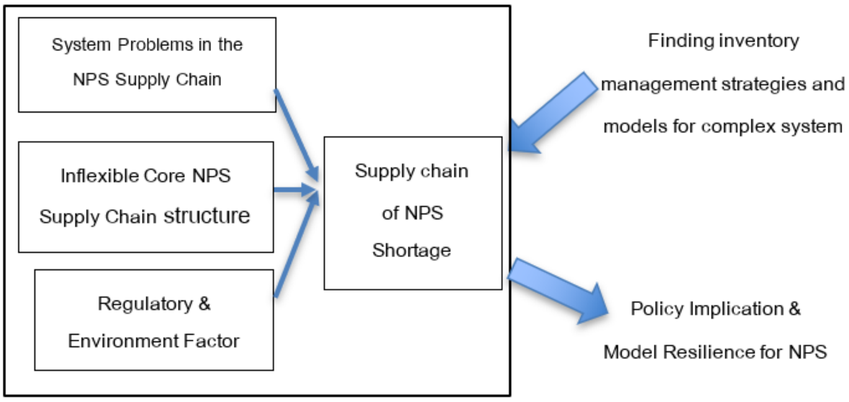

Figure 1. Research conceptual framework

shortages in the NPS supply chain. The retrieved models will be evaluated to identify the root causes of drug shortages, particularly those involving complex system such as feedback loops, regulatory limitations, and structural inflexibility. Therefore, inventory management strategies and system-level modeling are crucial tools for understanding these dynamics and guiding effective policy decisions. The framework for development of resilient, evidence-based approaches to managing the NPS supply chain is in Figure 1.

Methods

This study was conducted as a scoping review to analyze approaches for preventing drug shortages in NPS supply chain. The study protocol was approved by the Ethics Committee of the Ministry of Public Health. As this research was based exclusively on the review and synthesis of existing published literature, no direct involvement of human participants or identifiable personal data was required.

The review followed the five-step framework of Arksey and O'Malley (8, 9), which included identification of the research questions, identification of relevant studies, study selection, data charting and synthesis, as well as collation and reporting of the results (8, 10, 11).

Identifying the research question

First, we define a clear and focused research question that guides the scope of the review. We utilized frameworks such as PCC (population, concept, context) (10, 12) to structure the question, ensuring that it is broad enough to capture the scope of the existing literature while remaining specific enough to focus on the topic. The scoping review question was structured using the PCC elements. (Table 1)

We investigate the following broad research questions (RQs).

RQ1: What major themes have been identified in prior research addressing drug shortages in PSCs?

RQ2: What are the strategies for optimizing drug supply chain management to ensure consistent availability and minimize shortages?

RQ3: What modeling approaches are suitable for addressing drug shortages in the NPS supply chain as a complex system?

Table 1. Formulation of a scoping review using the "PCC element"

PCC element	elements in the title
population	"narcotic and psychotropic substance (NPS) supply chains"
concept	"inventory management strategies and system level modeling approaches for complex supply chains"
context	"understanding and mitigating drug shortages in highly regulated pharmaceutical systems"

Identifying relevant studies

In the second step of scoping review, we searched four electronic databases (PubMed, Web of Science, Science Direct, and IEEE). Search terms with Boolean operators were ("narcotic*" OR "psychotropic substance*" OR "controlled substance*" OR "NPS") and ("shortage*" OR "stock-out*" OR "drug shortage*" OR "medicine shortage*") AND ("mitigat*" OR "prevent*" OR "resilien*") AND ("inventory management" OR "inventory model*" OR "supply chain management" OR "SCM" OR "logistics" OR "forecasting" OR "predictive model*" OR "simulation")

Study selection

Inclusion criteria for studies included 1) original qualitative and/or quantitative research, 2) studies with focus on optimizing the drug supply chain, 3) articles with the adequately described research design and results, and 4) articles in English published in peer-reviewed journals, conference papers, and gray literature between 2000 and 2024. Exclusion criteria included studies not related to supply chain modeling or related strategies, publications in languages other than English and those with focus on supply chains outside pharmaceutical industry.

The process of selecting and reviewing studies was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses-Scoping Reviews (PRISMA-ScR) checklist, ensuring a systematic and consistent approach to identifying, evaluating, and reporting the included studies. All retrieved records were imported into the Rayyan program for de-duplication and screening. Two reviewers independently conducted a pilot screening to ensure consistency, followed by independent title/abstract and full-text screening according to predefined inclusion and exclusion criteria. Disagreements were resolved through discussion or consultation with a third reviewer.

The analysis was conducted according to a standard scoping review framework by Arksey and O'Malley (9) and the PRISMA-ScR guidance (13, 14). As illustrated in Figure 2, the PRISMA_ScR flow diagram outlines the criteria, process of study selection, and eligibility assessment. During the identification phase, 4,202 records were retrieved. After removing duplicates, 2,514 records remained for screening. A total of 2,474 records were excluded after title and abstract examination, primarily because they addressed general pharmaceutical logistics, hospital operations, clinical drug utilization, or non-model-based discussions without explicit focus on inventory strategies or system-level approaches to shortage mitigation. Of these, 16 were excluded due to insufficient methodological detail, lack of relevance to drug shortage mitigation, or absence of modeling or strategic analysis components. Ultimately, 29 studies met the eligibility criteria and were included in the final synthesis. Among the 29 included studies, none specifically examined NPS supply chains. All studies focused on PSCs more broadly. However, given that NPS supply chains operate within highly regulated and structurally constrained environments, the modeling approaches and inventory management strategies identified in these studies were considered conceptually transferable.

Charting data

The fourth step of scoping review or data charting is a critical step in which researchers systematically extract and organize relevant information from the included studies. This process involves creating a structured framework to collect, summarize, and categorize data that addresses the research question. To perform this step, we use a standardized charting form or table to ensure consistency in data collection. The charting form includes the following components: study details (e.g., author, year, location), overview, challenges and mitigation of PSC, themes relevant to the review questions, and key finding.

Collating, summarizing, and reporting

The final stage of the scoping review, collating, summarizing, and reporting the results, is a critical

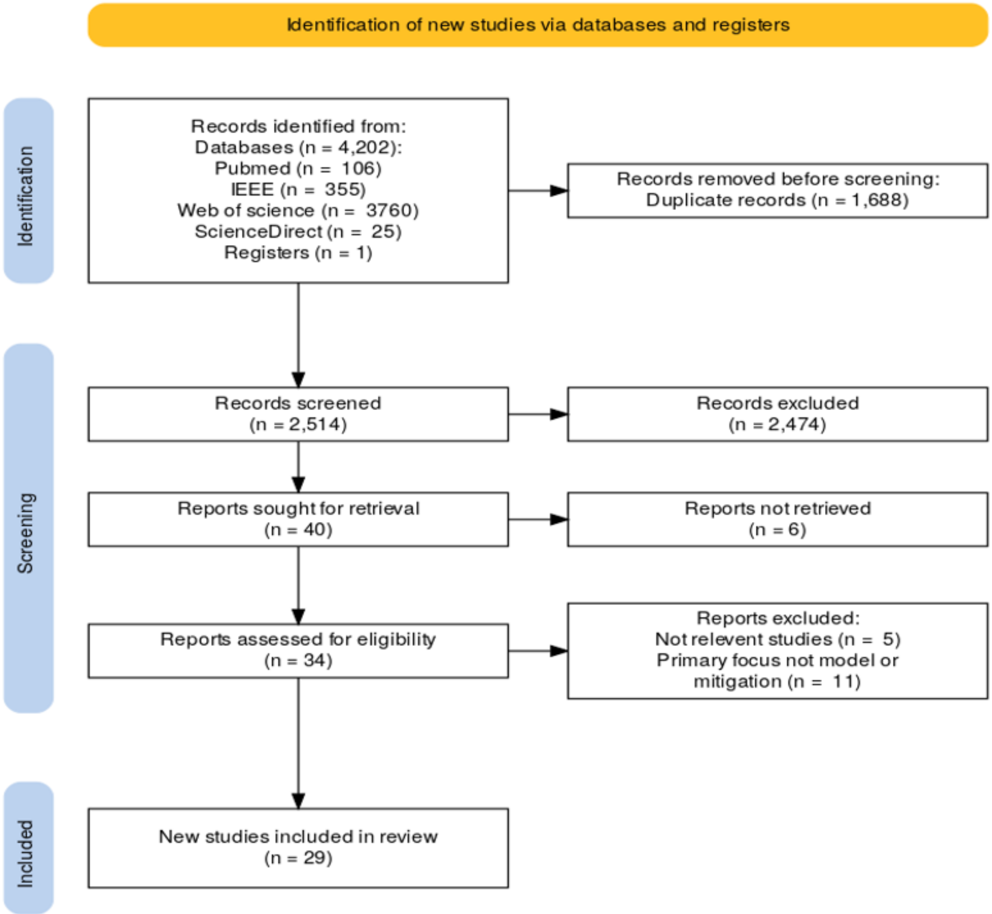

Figure 2. the PRISMA_ScR flow diagram summarizes the criteria

component of the review process. This stage involved synthesizing data extracted from the selected studies to give a complete overview of the current literature, identify key thematic patterns, and highlight gaps in current knowledge. The data collected during the extraction phase were first organized into a structured and usable format to facilitate systematic analysis. Data analysis was conducted using a combination of descriptive, quantitative, and qualitative approaches. Descriptive analysis was employed to summarize key study characteristics, including publication trends and research focus. Quantitative analysis was used to examine the distribution of studies across thematic clusters by calculating frequencies and percentages. In parallel, a thematic analysis was performed to identify, code, and group recurring concepts related to inventory management strategies, modeling approaches, digital technologies, and policy considerations.

Result

Characteristics of studies

Examining publication trends shows several important patterns in the development of research aimed at improving PSC management. Although work in this field began as early as 2017, the amount of research has grown significantly in recent years. No relevant studies were found between 2008 and 2013 or in 2016. In contrast, a marked growth in publications was observed after 2019, with more than 22 studies published between 2020 and 2024. Overall, only two articles were published prior to 2015, whereas the majority of the included studies (n = 27) were published between 2015 and 2024. This trend indicates a growing academic and policy interest in PSC optimization, likely driven by increasing concerns over drug shortages, supply chain disruptions, and the need for more resilient healthcare systems. Moreover, It may also be the evidence of changes in the pharmaceutical industry, such as market consolidation and mergers between large multinational companies, which can influence production concentration, pricing power, and supply chain vulnerability.

RQ1: Major themes

Identifying the themes involved a recursive process of becoming acquainted with the studies, followed by the generation and refinement of themes through repeated analysis of research questions, measured variables, and the main focus of each study. After carefully reviewing the studies, sixteen themes were identified in this scoping review, with some studies featuring multiple themes. (Table 2) The most common theme in pharmaceutical supply chain management was the blockchain-based framework in fourteen studies (15-28). System dynamics modeling was investigated in six studies (29-34). Five studies focused on causal loop diagrams (CLD) (29, 31, 33) and stock-flow diagrams (SFD) (29, 31). Other themes included the ABC-VED matrix analysis (35, 36), ABC-VEN analysis (37),

Table 2. Clusters of themes covered in the pharmaceutical supply chain literature.

cluster title	themes	number of studies
cluster 1	- system dynamics modeling: causal loop diagrams	7
system analysis and modeling for	(CLDs) and stock-flow diagrams	
complex supply chains		
cluster 2	- ABC-VEN matrix	1
inventory management strategies	- ABC-VED matrix analysis	2
and optimization	- inventory pooling theory	1
	- safety stock optimization SD modeling	1
	- vendor-managed-inventory (VMI)	1
	- mathematical models	1
	- ABC and VED analysis	1
cluster 3	- RFID technology	1
digital transformation and	- The SDDiP algorithm	1
technology adoption	- third party centralized integrated system (TPCIS)	1
	- serialized global trade item number (SGTIN)	
	- blockchain-based framework	1
	- blockchain assisted archimedes optimization with	11
	machine learning driven drug supply management	1
	(BAOML-DSM)	
	- RFID and QR codes technology	
		1
cluster 4	- policy options	1
policy, governance, and risk	- resiliency decisions	1
management	- policy implications from SD modeling	2
	- governance implications of cloud-based	1
	- security and governance using RFID systems	1

inventory pooling theory (30), vendor-managed-inventory (VMI) (38), mathematical model (the SDDiP algorithm) (39), blockchain assisted archimedes optimization with machine learning driven drug supply management (BAOML-DSM) (24), RFID and QR codes technology (27). One study included two themes i.e., third party centralized integrated system (TPCIS) and serialized global trade item number (SGTIN) (40). (Table 2)

The thematic analysis identified four clusters, each comprising 20 themes that explain how previous studies have addressed drug shortages in PSCs, particularly within complex, highly regulated systems. The first cluster represents system analysis and modeling for complex supply chains. This cluster focuses on understanding, simulating, and analyzing complex supply chain behavior driven by feedback loops, delays, and non-linear interactions. They directly support the identification of appropriate models for complex NPS systems. The second cluster represents inventory management strategies and optimization. This cluster reflects operational-level strategies used to mitigate drug shortages.

These approaches act as decision levers within system-based models and are commonly evaluated through simulation to assess their effectiveness under uncertainty. One cluster is related to digital transformation and technology adoption, focusing on the digital technologies as enabling mechanisms that enhance visibility, coordination, and data integration across supply chain stages. These technologies support system-based and inventory models but do not independently address system complexity. The last cluster represents policy, governance, and risk management, focusing on critical areas for linking modeling results to policy implications, particularly in highly regulated contexts such as the NPS supply chain.

The thematic analysis showed that digital transformation and technology adoption were the most frequently identified clusters (58.6%), followed by management strategies and optimization (27.6%). System analysis and modeling approaches accounted for 24.1% of the studies, while policy, governance, and risk management themes were least represented (20.7%). This distribution highlights a strong emphasis on technological solutions in the literature, alongside a relative gap in system-oriented and policy-integrated modeling approaches.

Figure 3 presents the thematic map based on centrality (relevance) and density (development),

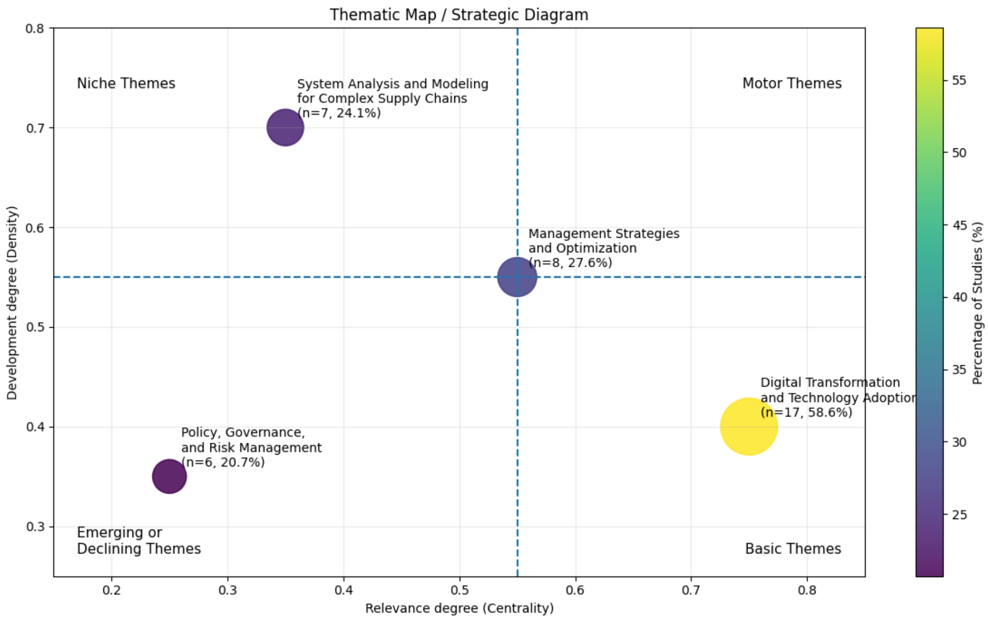

Figure 3. The thematic map/strategic diagram

derived from a co-word network analysis of standardized author keywords from the 29 included studies. Centrality was calculated as the normalized strength of external links between each thematic cluster and other clusters, indicating its structural importance within the overall research field. Density measured the internal cohesion of keywords within each cluster. Digital transformation and technology adoption emerged as the most central theme, positioned in the basic themes quadrant and representing the largest share of studies (58.6%). Management strategies and optimization function as a linking theme near the center, whereas system analysis and modeling for complex supply chains appears as a niche theme with strong internal development but lower cross-theme connectivity. Policy, governance, and risk management is located in the emerging or declining quadrant, reflecting limited integration within the broader research landscape.

Comparison of selected studies focusing on inventory management strategies and system-based models indicates that most studies adopted system-oriented approaches, particularly system dynamics and simulation-based models, to capture interactions among supply chain components. Several studies also applied traditional inventory techniques, such as safety stock policies and ABC analysis, to support operational decision-making. A detailed summary of the reviewed studies is presented in Table 3.

RQ2: Strategies to minimize shortages

Optimizing drug supply chains to address shortages is a complex challenge that has been the focus of numerous research studies. Table **4** shows challenges and mitigation strategies on optimizing drug supply chains. One study reported the significance of addressing drug shortages through improved supply chain management and the development of mathematical models to inform policy decisions (39). Six studies focused on system dynamics simulation models developed to analyze supply chain performance at various healthcare facilities (29-34). One study showed that the third party centralized integrated system (TPCIS) addressing issues of counterfeit, diverted drugs, and drug shortages in PSC and improved data sharing can enhance the efficiency of drug recall processes and mitigate drug shortages (40). A novel technique called blockchain-assisted Archimedes optimization with machine learning-driven drug supply management (BAOML-DSM) enhances drug supply chain management. It utilizes Hyperledger Fabric to manage the drug supply chain, improving tracking procedures within a smart pharmaceutical environment (24). Three studies combining the ABC and VED analysis were highlighted as essential for better management and prioritization of drug supplies (35, 36, 41). The ABC-VEN analysis is considered a practical method for optimizing the PSC. The national essential medicines list is recommended based on ongoing ABC-VEN analysis (37). One study focusing on vendor-managed-inventory (VMI) and consignment stock (CS) policies for enhancing inventory management between supply chain components (38). The last study for reducing shortages and optimizing inventory decisions focused on diffusion models (43).

Mathematical models

Four mathematical models to address pharmaceutical drug shortages caused by supply chain disruptions were identified. The static optimization models, SCDD and SCDD-I, utilize stochastic programming to demonstrate that profit-maximizing firms often select vulnerable supply chains for generic oncology drugs like vinblastine and vincristine, However, policies mandating redundancy or specific inventory levels can effectively incentivize resilience. Building on this, the D-SCDD model applies stochastic dual dynamic integer programming within a dynamic framework, revealing that reducing the lead time to add new components (e.g., from 1 year to 3 months) significantly lowers shortage risk and prevents market

Table 3. Summary of reviewed studies

no.	author/ year	country	overview	mitigation of PSC	focus
1	Rahman, et al., 2025 (15)	India	**Objective**: To improve traceability throughout the drug supply chain **Summarize:** The key problem of drug counterfeiting and how blockchain technology can help improve transparency, tracking, and security in the drug supply chain.	blockchain-based framework	drug counterfeiting
2	Hoai Luan, et al., 2019 (16)	Japan.	**Objective**: To suggest an innovative anti-counterfeit medication system utilizing Ethereum blockchain networks to improve real-world utility. **Summarize:** A novel anti-counterfeit medicine system designed to resist drug cloning and enhance practical applicability	blockchain-based framework	anti-counterfeit medicine
3	Ahmadi, et al., 2020 (17)	China	**Objective**: To provide a transformation of the current PSC by incorporating tracking technologies **Summarize:** IoT-based blockchain system aims to track drug transportation, prevent theft, and verify the provenance of medicines	IoT and blockchain technology	counterfeit drugs
4	Saindane, et al., 2020 (18)	India	**Objective**: To leverage blockchain technology to enhance the transparency, security, and traceability of the PSC, related to counterfeit drugs **Summarize:** The blockchain's potential to reduce counterfeiting, improve compliance with regulations, and lower operational costs through smart contracts.	IoT and blockchain technology	reduced Counterfeits
5	Musamih, et al., 2021 (19)	United Arab Emirates	**Objective**: To develop and Assess a blockchain-based solution for drug traceability within PSCs. to prevent counterfeit drugs **Summarize:** A blockchain-powered system for tracking pharmaceuticals within healthcare supply chains, counterfeit medications, and improving transparency.	blockchain-based framework	counterfeit drugs

Table 3. Summary of reviewed studies (continued)

no.	author/ year	country	overview	mitigation of PSC	focus
6	Akram, et al., 2024 (20)	India	**Objective**: To highlight the importance and necessity of blockchain technology for PSC management systems. **Summarize:** Reviews the importance of blockchain technology in strengthening the PSC, highlighting its potential to enhance traceability, security, and transparency.	blockchain-based framework	counterfeit drugs,
7	Humayun, et al., 2022 (21)	Saudi Arabia	**Objective**: To optimize the drug distribution process (DDP), a framework for drug distribution is proposed. **Summarize:** Enhancing security and coordination in the drug distribution market (DDM) to combat issues like counterfeit drugs and coordination failures. Implementations are planned to assess the effectiveness of the proposed blockchain system.	blockchain-based framework	drug distribution
8	Abdallah, Nizamuddin, 2023 (22)	United Arab Emirates	**Objective**: To propose a blockchain-based framework for the online sale of pharmaceutical products, aiming to enhance transparency in the supply chain **Summarize:** Blockchain-based framework for the PSC, addressing issues of transparency and trust among manufacturers, suppliers, and consumers	blockchain-based framework	enhance transparency and trust within the pharma supply chain.
9	Gaynor, et al., 2024 (23)	USA	**Objective**: To identify and evaluate the most suitable blockchain applications in the pharmaceutical industry using an extended 4D framework **Summarize:** The analysis ranked nine blockchain applications and preventing prescription drug misuse and counterfeit sales	blockchain-based framework	drug misuse and abuse prevention, prevention of counterfeits
10	Shanthi, Venkatesh 2023 (24)	India	**Objective**: To develop a blockchain-assisted Archimedes optimization combined with machine learning-driven drug supply management (BAOML-DSM) method for the pharmaceutical industry.	blockchain-based framework with machine learning	optimizing supply chain, tracking and traceability

Table 3. Summary of reviewed studies (continued)

no.	author/ year	country	overview	mitigation of PSC	focus
			Summarize: Blockchain Assisted Archimedes Optimization with Machine Learning Driven Drug Supply Management (BAOML-DSM), enhancing drug supply chain management in the pharmaceutical sector.		
11	Crossland, et al., 2023 (25)	USA	**Objective**: To design a trustless and scalable system for PSC that ensures end-to-end visibility to prevent counterfeit drugs **Summarize:** A blockchain-based pharmaceutical track-and-trace system designed to prevent counterfeit products from entering the PSC.	blockchain-based framework	counterfeit drugs
12	Kumar, et al., 2023 (26)	India	**Objective**: To develop a smart health supply chain management system by integrating Blockchain technology with IoT to enhance security, efficiency, and transparency in the supply chain **Summarize:** The Novel Approach for Integrated IoT with Blockchain in Health Supply Chain (NAIBHSC) effectively addresses significant challenges in the healthcare supply chain, such as security, transparency, and counterfeit drugs.	the novel approach for integrated iot with blockchain in health supply chain (NAIBHSC)	security, transparency, and counterfeit drugs
13	Shah, et al., 2022 (27)	USA and India	**Objective**: To introduce blockchain technology as a solution for enhancing transparency and traceability in PSCs **Summarize:** The study implements blockchain technology in PSC management to enhance transparency, traceability, and security using RFID and QR codes for real-time drug tracking and counterfeit reporting.	blockchain-based framework by RFID and QR codes	drug counterfeiting drug traceability
14	Bapatla, et al., 2024 (28)	India	**Objective**: To propose a novel solution using a Blockchain Enabled QR Code mechanism for efficient tracking and tracing of pharmaceuticals	blockchain-based framework	drug counterfeiting and improve supply

Table 3. Summary of reviewed studies (continued)

no.	author/ year	country	overview	mitigation of PSC	focus
			Summarize: Blockchain technology in PSC management to enhance transparency, traceability, and security		chain efficiency
15	Kumar, Kumar, 2014 (29)	India	**Objective**: To using system dynamics techniques to assist policymakers in improving the sustainability and efficiency of the supply chain **Summarize:** Causal loop diagrams (CLD) and stock-flow diagrams (SFD) using system dynamics techniques for improved inventory management	system dynamic modeling	stock shortages
16	Wu. et al., 2015 (30)	China	**Objective**: To demonstrate the effectiveness of Inventory Pooling theory in improving drug supply chain performance, particularly in reducing shortages **Summarize:** Inventory Pooling is an effective method to enhance drug supply and procurement performance, significantly reducing supply shortages	system dynamic modeling	supply shortages
17	Kumar, Kumar, 2015 (31)	India	**Objective**: To develop a system dynamics model to simulate the supply chain. **Summarize:** Causal loop and stock-flow diagrams by the system dynamic modeling to illustrate cause-effect, incorporating safety stock to mitigate stockouts	system dynamic modeling	mitigate stockouts
18	Bam, et al., 2017 (32)	South Africa	**Objective**: To develop a systems dynamics simulation model to evaluate the supply to minimize shortages and costs **Summarize:** A system dynamics model optimizes safety stock policies to improve supplier lead times, inventory management, and reduce shortages and costs.	system dynamic modeling	reduce shortages and costs

Table 3. Summary of reviewed studies (continued)

no.	author/ year	country	overview	mitigation of PSC	focus
19	Kochan, et al., 2018 (33)	USA	**Objective**: To examine cloud computing as an enabler of electronic supply chain management systems (e-SCMs) to enhance collaborative hospital supply chains **Summarize:** The impact of cloud-based information sharing on hospital supply chain using a SD framework, finding that reducing inventory costs and shortages.	system dynamics and causal loop diagrams	reduce inventory costs and shortages
20	Jenzer, et al., 2021 (34)	Switzerland,	**Objective**: To address the challenge of medicine shortages and to explore innovative approaches to manage supply chains, particularly through system dynamics simulation **Summarize:** Innovative approach combining expert interviewing and system dynamics simulation is proposed for managing supply chains effectively.(34, 39)	system dynamics simulation	medicine shortages
21	Kant, et al., 2015 (35)	India	**Objective**: To explore the optimal drug inventory management technique suitable for a secondary care hospital **Summarize:** The ABC-VED matrix proved to be an effective system for ensuring drug availability and optimizing resource use in secondary healthcare settings.	ABC, VED and ABC-VED matrix	drug availability and management efficiency
22	Guru, et al., 2024 (36)	India	**Objective**: To integrate ABC and VED analysis to categorize drugs based on consumption patterns. **Summarize:** The ABC-VED matrix proposed a comprehensive framework for effective resource allocation and inventory management it is crucial for preventing stockouts and ensuring the availability of essential medications.	ABC and VED analysis	stockouts and availability of essential medications
23	Mfizi, et al., 2023 (37)	Rwanda	**Objective**: To analyze the inventory management of essential generic medicines distributed using ABC-VEN analysis **Summarize:** Analyzes pharmaceutical inventory management using ABC-VEN analysis	ABC-VEN analysis	optimizing supply chain

Table 3. Summary of reviewed studies (continued)

no.	author/ year	country	overview	mitigation of PSC	focus
			practical method for optimizing the PSC.		
24	Lotfi, et al., 2024 (38)	Iran	**Objective**: To propose a new viable supply chain (VSC) that integrates vendor-managed inventory (VMI) with a consignment stock (SC) policy to enhance inventory management between supply chain components **Summarize:** Integrating VMI and CS policies within a viable supply chain (VSC) significantly reduces costs, achieving a 14.8% reduction compared to scenarios without these strategies	vendor-managed-inventory (VMI) and consignment stock (CS) policies,	reduces costs
25	Tucker, 2020 (39)	USA	**Objective**: To study resiliency decisions for the highly regulated supply chains of generic injectable drugs **Summarize:** New supply chain design models that account for disruptions and recovery, aiming to enhance the resilience of drug supply chains.	mathematical models	drug shortages
26	Choi, et al., 2015 (40)	USA	**Objective**: To improve traceability and visibility among trading partners **Summarize:** A third party centralized integrated System to overcome existing barriers and improve drug supply chain security	the third party centralized integrated system (TPCIS)	counterfeit, and drug shortages
27	Jaju et al., 2023 (41)	India	**Objective**: To identify drugs that require stringent management control through the application of inventory analysis techniques **Summarize:** ABC and VED analysis improved supply chain management and proposed solutions such as adopting bar code technology and integrating electronic health records with inventory systems	ABC and VED analysis	optimizing supply chain

Table 3. Summary of reviewed studies (continued)

no.	author/ year	country	overview	mitigation of PSC	focus
28	King, Zhang, 2007 (42)	USA	**Objective**: To reduce counterfeiting while preserving privacy **Summarize:** RFID technology is applied to enhance supply chain integrity through anti-counterfeiting detection	RFID technology	tracking and authenticating drugs, counterfeiting
29	Eapen, 2024 (43)	USA	**Objective**: To develop and evaluate diffusion-based predictive models to prevent shortages caused by supply–demand imbalances. **Summarize:** The study applies diffusion models, particularly the Bass model, to historical sales data to improve drug supply forecasting, to reduce shortages, optimize inventory decisions, and enhance PSC resilience.	diffusion models	reduce shortages, optimize inventory decisions

exits for vincristine. Finally, the SCR model provides closed-form analytical equations to evaluate existing supply chain configurations, showing that adding a backup supplier is far more effective at reducing expected shortages (from 10% to 4%) than adding a backup manufacturing line (39).

System dynamic modeling

System Dynamics (SD) modeling effectively mitigates drug shortages by simulating complex supply chain feedback loops to identify bottlenecks and test optimization policies before implementation. For instance, Kumar and Kumar used SD to analyze the rural distribution of folic acid in India, demonstrating that establishing calculated safety stocks at every supply chain stage could reduce stock-outs caused by uncertain lead times. Similarly, Bam et al. applied SD to the amikacin supply chain in South Africa, simulating 141 scenarios to reveal that preferentially selecting suppliers with shorter lead times and adopting constant safety stock policies were significantly more effective than mere overstocking in minimizing shortages and operational costs (29-34).

Third party centralized integrated system

The third party centralized integrated system (TPCIS) mitigates drug shortages by establishing a centralized database for real-time inventory visibility and implementing a "drug shortage early alert system". This system allows manufacturers to detect pending stock-outs at the wholesaler level and immediately shorten production lead times to proactively replenish supply, rather than waiting for delayed orders. For example, simulations comparing this integrated approach to a traditional, disjointed supply chain ("AS-IS") demonstrated that the TPCIS reduced the average number of drug shortage cases in pharmacies by 85% (from 24,918 to 3,647) by enabling faster responsiveness to demand fluctuations (40).

Table 4. Challenges and mitigation strategies for availability and minimizing shortages

challenges and mitigation strategies	number of studies (reference)
mathematical models	1 (39)
system dynamic modeling	6 (29-34)
third party centralized integrated system (TPCIS)	1 (40)
blockchain-based framework with machine learning	1 (24)
ABC and VED analysis	3 (35, 36, 41)
ABC-VEN analysis	1 (37)
vendor-managed-inventory (VMI) and consignment stock (CS) policies	1 (38)
diffusion models	1 (43)

Blockchain-based framework

The blockchain assisted Archimedes optimization with machine learning driven drug supply management (BAOML-DSM) model mitigates drug shortages by integrating the Hyperledger Fabric blockchain for secure, real-time supply chain tracking and using a gradient boosting decision tree (GBDT) algorithm to optimize drug recommendations and inventory management. This system enhances visibility into drug flows, enabling stakeholders to quickly identify supply interruptions and recover from them more efficiently than with traditional methods. For example, by using the Archimedes optimization algorithm (AOA) to fine-tune parameters, the model achieved a superior prediction accuracy of 96.68% on benchmark datasets, significantly outperforming the other methods like support vector machine (95.42%) and random forest (95.16%), thereby ensuring more precise demand matching and reducing the administrative inefficiencies that lead to stock-outs (24).

ABC and VED analysis

The ABC (Always Better Control) and VED (Vital, Essential, Desirable) analyses were used to categorize drugs based on their expenditure and clinical importance (35). ABC analysis classifies inventory items based on their budget expenditure. It helps identify which items consume the most resources and require the most attention. Drug items are arranged by total expenditures in descending order and cumulative costs are calculated. Group A is high-value items that account for a significant portion of the total cost. Group B is moderate-value items. Group C or low-value items account for a small portion of the total cost.

The ABC-VED matrix analysis was conducted to further classify drugs into three categories to enhance inventory control. The use of systematic inventory control methods, such as ABC and VED analysis, was highlighted as essential for better management and prioritization of drug supplies (41). It emphasized the importance of integrating inventory control techniques, specifically ABC and VED analysis, to ensure the availability of essential medications while optimizing resource utilization (36). The ABC-VED matrix proposed a comprehensive framework for effective resource allocation and inventory management prioritization, balancing financial and clinical factors (35, 36, 41).

ABC-VEN analysis

VEN analysis was conducted using expert judgment by categorizing products according to their impact on public health. It categorizes items into Vital (V) or items essential for survival and critical for health, Essential (E) or items necessary for basic health services, and non-essential (N) or Items that are not critical for the health service. The combination of ABC and VEN analyses, known as ABC-VEN, provides a comprehensive approach to inventory management by considering both the cost and the criticality of the items. This method is particularly useful for identifying products that require strict control and ensuring that vital and expensive products are carefully monitored to prevent shortages (37).

VMI and Consignment Stock policies

A new viable supply chain (VSC) model integrates vendor-managed-inventory (VMI) with a consignment stock (CS) policy to enhance inventory management in the healthcare industry. This integration is facilitated through a hybrid robust stochastic optimization (RSO) technique, which incorporates robustness and risk criteria into the objective function to ensure optimal solutions. Reduction in costs was greater when VMI and CS were included in the problem-solving approach, compared to scenarios without these strategies. This highlights the effectiveness of these methods in reducing supply chain cost (38).

Diffusion models

Diffusion models enhance drug supply forecasting by capturing how medicine demand evolves over time in response to external drivers and adoption behavior. By anticipating demand growth and turning points, these models support proactive production planning, inventory optimization, and early mitigation of drug shortages, thereby enhancing supply chain resilience (43).

A three-dimensional gap analysis shows that the current literature on this issue has some structural problems. First, the methodological gap shows that modeling approaches are not well integrated. For example, optimization models often focus on operational efficiency under rigid baselines, while SD models focus on policy dynamics with significant feedback. However, there isn't much integration between these two approaches, and hybrid approaches are still not fully developed. Second, the policy-relevance gap shows that significant amounts of research remain theoretical or based on simulations and don't directly connect model structures to real-world regulatory tools, such as rules for allocating quotas, timelines for licensing, or mechanisms for enforcement. This makes it more difficult for decision-makers to use the research. Third, the context gap shows that most studies have been conducted in developed pharmaceutical markets, and there aren't many real-world examples of how NPS systems work in highly regulated developing countries. This lack of balance in the context makes it challenging to apply the findings to other situations and underscores the importance of modeling based on each country's rules.

RQ3: suitable approaches for NPS supply chain

Results from the included studies show that drug shortage issues are inherently complex and cannot be fully explained by single-factor or static approaches. The literature consistently shows that shortages emerge from the interaction of multiple process-level and policy-level factors, including regulatory constraints, inventory control policies, demand variability, supply disruptions, and information delays. These interactions often generate non-linear system behavior and delayed effects, which are difficult to capture using conventional analytical models.

Across the reviewed studies, traditional inventory management strategies, such as reorder point policies, Economic Order Quantity (EOQ), and safety stock calculations, were the most frequently used approaches to address operational inefficiencies. These methods were primarily used to optimize inventory levels and reduce stockouts under relatively stable conditions. However, the findings also indicate that these strategies are limited in highly regulated NPS supply chains, where long approval processes, regulatory lead times, and multi-agency governance significantly influence system behavior and constrain rapid adjustment of inventory policies. The review further identified the application of technology-driven approaches, including blockchain-based traceability, artificial intelligence, demand forecasting, and cloud-based information-sharing systems. These approaches were primarily used to enhance data availability, transparency, and coordination across various supply chain stages. Studies reported that improved information sharing could reduce inventory costs, enhance responsiveness, and support more accurate demand forecasting.

On the other side, a smaller but conceptually important group of studies has used SD modeling to resolve problems in PSCs. The significance of SD lies not solely in simulation outputs but also in its clear representation of feedback loops, time delays, and regulatory interactions through causal loop and stock-flow frameworks. Agent-based modeling (ABM) is appropriate for complex adaptive systems, especially for representing diverse actor behaviors. However, SD is more suitable for issues related to combined policy feedback, quota systems, and system-wide regulatory delays, as seen in NPS supply chains. SD models represent system structure through causal loop diagrams (CLDs) and stock–flow diagrams (SFDs), enabling visualization of feedback loops, delays, and interdependencies across supply chain stages (29-34). Several studies have demonstrated the use of SD models to simulate inventory levels and stockouts over time**.** The findings suggest that SD modeling can effectively support decision-making by enabling policymakers to test alternative inventory and regulatory scenarios prior to implementation. The reviewed SD studies consistently highlighted the role of system-level modeling in supporting policy and strategic decision-making (29-34). By capturing the mutual relationships among demand fluctuations, order rates, inventory levels, and regulatory delays, SD models enable policymakers to better understand how interventions at one stage of the system can produce unintended effects at other stages. Moreover, SD-based approaches were shown to be particularly useful for informing long-term policy decisions aimed at enhancing the sustainability and resilience of healthcare supply chains (**29**).

This scoping review provides a system-oriented understanding of how drug shortages have been addressed in PSCs and highlights important implications for highly regulated contexts such as the NPS supply chain. Although the thematic analysis shows that digital transformation and blockchain-based approaches constitute the largest share of the literature (58.6%), proportion of publication reflects current technological trends rather than methodological fitness for structurally regulated systems. Most blockchain-oriented studies emphasize transparency, traceability, and anti-counterfeiting, which are critical to information integrity but primarily address visibility issues. In contrast, NPS supply chains are structurally shaped by quota allocation, licensing procedures, multi-agency approvals, and security controls that generate endogenous time delays, feedback loops, and adaptive regulatory responses. These dynamics influence availability through mechanisms such as approval backlogs, demand–quota mismatches, and policy resistance—phenomena that cannot be fully captured by visibility-enhancing technologies alone. Therefore, while digital and blockchain tools address operational transparency, SD is methodologically more suitable for modeling the causal structure, feedback effects, and long-term policy impacts that characterize highly regulated NPS systems. This explains why methodological appropriateness may diverge from publication dominance.

SD model in supply chain challenges

Inventory control models such as SD model could be applied to maintain the optimum quantity of medicine at each stage of the supply chain. This could help balance supply and demand effectively, thereby reducing instances of stockouts and ensuring patients have access to the medications (32).

SD is also used to develop conceptual CLDs that represent both traditional and cloud-based information-sharing models in hospital supply chains (33). The findings indicate that cloud-based information sharing can reduce inventory costs and prevent healthcare supply shortages by providing more accurate demand forecasts. Additionally, it significantly improves visibility and responsiveness in healthcare supply chains, leading to reduced costs and shortages (33). Overall, the results indicate that while traditional inventory management strategies and digital technologies contribute to operational improvements, they are insufficient for addressing drug shortages as a complex system problem. SD modeling emerges as the most suitable modeling approach for understanding, simulating, and analyzing drug shortages in the NPS supply chain, as it explicitly captures interrelated process- and policy-level factors and supports policy-oriented decision-making in highly regulated environments.

Discussion

This review shows that digital transformation and blockchain-based approaches account for the largest share of the literature (58.6%). However, their popularity reflects current research trends rather than their suitability for highly regulated NPS systems. All digital techniques aim to make information more accessible and easier to find. However, quota controls, licensing delays, and regulatory feedback mechanisms that cause time delays and policy resistance shape the availability of NPS drugs. SD is important because it allows for internal feedback and regulatory relationships, which is the reason methodological suitability may be different from publication dominance. For example, while blockchain may provide real-time tracking of drug flows, it does not explain how delays in quota approval or restrictive regulatory responses to perceived risk may unintentionally amplify shortages, a phenomenon commonly described as policy resistance.

In contrast, although SD modeling represents a smaller proportion of the reviewed studies (24.1%), it directly addresses the structural and dynamic characteristics of complex systems. SD explicitly captures feedback loops, time delays, non-linear relationships, and policy resistance, enabling the analysis of how well-intentioned regulatory or inventory interventions may produce counterintuitive outcomes over time. Although general supply chain tools such as ABC analysis, EOQ, blockchain, and system-level modeling are widely reported in the literature, their application in NPS supply chains must be interpreted within strict regulatory constraints, including quota systems, licensing requirements, and mandatory reporting. SD allows for the integration of both process-level dynamics (e.g., ordering, stock replenishment, and distribution) and policy-level constraints (e.g., regulatory approvals and security controls). Importantly, the reviewed studies emphasize that the value of SD modeling lies not only in quantitative simulation outputs but also in the modeling process itself. The development of causal loop diagrams and stock–flow structures facilitates a shared understanding among stakeholders, including regulators, supply chain managers, and policymakers. This participatory aspect is particularly relevant for NPS supply chains, where multiple agencies with distinct mandates must coordinate decisions under strict regulatory oversight. Despite its strengths, the application of SD modeling also presents several limitations that warrant critical consideration. First, SD models are highly dependent on the availability and quality of data. In NPS supply chains, data may be fragmented across regulatory agencies, incomplete, or subject to confidentiality constraints, which can limit the accuracy of models. Second, model calibration can be challenging due to long and variable lead times, regulatory uncertainty, and limited historical data on rare but impactful shortage events. Third, SD models may encounter policy resistance, where stakeholders are reluctant to accept model-based recommendations that challenge established regulatory practices or institutional norms. In highly controlled NPS systems, proposed changes, such as adjusting quotas or streamlining licensing processes, may face resistance due to concerns over misuse, diversion, or legal compliance. These challenges underscore the importance of combining SD modeling with stakeholder engagement and transparent communication to enhance model credibility and policy acceptance.

The findings of this scoping review have important implications for Thailand's NPS supply chain, which operates under a highly centralized and tightly regulated system governed by the Thai Food and Drug Administration and the Narcotics Code. In Thailand, NPS procurement, importation, distribution, and reporting are regulated through quota approvals, licensing, and mandatory reporting requirements, which aim to prevent diversion but also introduce significant administrative delays and inflexibility. Within this context, digital technologies such as blockchain could support regulatory compliance by improving traceability, auditability, and real-time reporting to the Thai FDA, potentially reducing the administrative burden associated with drug movement records and annual quota reconciliation. However, these technologies alone cannot address structural delays arising from approval cycles, conservative quota-setting, or emergency supply adjustments, which are central challenges in the Thai NPS system.

SD modeling offers a more suitable framework for the Thai context. This simulation models how Thai regulatory policy decisions interact with hospital demand, inventory, and supplier lead times. It specifically addresses a centrally governed quota system, similar to other highly regulated NPS regimes that involve annual production quotas, licensing, and mandatory reporting. Although the reviewed studies mainly focus on international supply chains, they examine regulatory environments with centralized oversight and controlled distribution—structures that closely resemble Thailand's framework. Therefore, applying these modeling approaches to the Thai context is justified, provided that local regulatory parameters and institutional details are explicitly integrated.

Although the goal of this scoping review was to map the range of current strategies for responding to drug shortages, the search strategy primarily focused on terms related to problem-solving and reducing problems. Consequently, studies focusing specifically on root-cause analysis or structural drivers—without relating their research to "mitigation," "resilience," or comparable intervention terminology—may have been underrepresented. Even though this doesn't change the overall patterns found, it might help explain why technology-driven and solution-focused approaches were so common in the dataset. Therefore, the findings should be considered a guide to the current publication frameworks rather than a comprehensive representation of system-level analyses. Future reviews could enhance coverage by systematically integrating causal and driver-focused search terms. SD modeling has advantages for understanding feedback structures and policy resistance, but hybrid modeling approaches might be even better. For instance, combining SD with stochastic or multi-echelon optimization models could improve the accuracy of operational decisions and policy-level scenario testing. Hybrid frameworks may be particularly useful for NPS supply chains, where regulatory controls and inventory optimization need to be evaluated together. For researchers, the findings highlight the need for further empirical applications of SD modeling in NPS contexts, particularly studies that integrate regulatory data and examine long-term policy impacts. Strengthening this line of research could contribute to more resilient, transparent, and responsive NPS supply chains.

This review purposefully focused on strategies for mitigation, prevention, and resilience to address drug shortages, rather than analyzing structural causes or consequences. The high number of excluded records is due to the use of specific inclusion criteria that require specific inventory management or system-modeling components, not mistakes made during the search. While specific keywords ensured the study was relevant to the goal, future research might use additional structural and policy-related terms to offer another perspective. Furthermore, most information on NPS supply chains is derived from general pharmaceutical literature, which may not be directly relevant to this situation. These limitations suggest the importance of future qualitative modeling studies based solely on NPS regulatory and operational data. The limitation to English-language and pharmaceutical-related publications may inadequately represent gray literature and regulatory reports, especially from NPS authorities in developing countries such as Thailand.

SD modeling is particularly suitable for analyzing drug shortages in highly regulated supply chains because it captures feedback loops, time delays, and non-linear interactions among supply, demand, inventory, and regulatory controls. Lacking a system-level perspective, policymakers risk overestimating the efficacy of quota restrictions while underestimating administrative delays. They may also fail to anticipate compensatory behaviors, such as stockpiling, which can exacerbate shortages under strict regulations. Therefore, future research should focus on developing SD models that integrate operational processes, inventory policies, and regulatory mechanisms. Such models would facilitate scenario testing, thereby mitigating the risk of unintended policy consequences

Conclusions

This scoping review synthesizes existing evidence on inventory management strategies, analytical models, and technological approaches developed to mitigate drug shortages in PSCs, with relevance to highly regulated contexts such as the NPS supply chain. The findings suggest that drug shortages are the result of a complex interplay of several factors, including regulatory constraints, operational procedures, information flow, and demand–supply uncertainties, rather than isolated issues. Although traditional inventory management methods, such as safety stock policies and ABC analysis, are still helpful for operational decisions, they often fall short when used alone in complex situations. Digital technologies, including blockchain, artificial intelligence, and cloud-based information sharing, improve visibility and coordination but primarily function as enabling tools rather than comprehensive solutions. Overall, the review suggests that SD modeling is particularly well-suited for addressing drug shortages in complex pharmaceutical systems, as it facilitates the understanding, simulation, and analysis of interrelated process- and policy-level factors, providing a valuable foundation for evidence-based policy and inventory decision-making.

Acknowledgements

This article is part of the doctor of philosophy program in pharmaceutical sciences and health, faculty of pharmacy, Thammasat university

References

1. Shukar S, Zahoor F, Hayat K, Saeed A, Gillani AH, Omer S, et al. Drug shortage: causes, impact, and mitigation strategies. Front Pharmacol. 2021; 12: 693426.
2. Ventola CL. The drug shortage crisis in the United States: causes, impact, and management strategies. P T. 2011; 36: 740-57.
3. Gallego-García D, Gallego Garcia S, García-García M. An optimized system to reduce procurement risks and stock-outs: A simulation case study for a component manufacturer. Appl Sci. 2021; 11: 10374.

4. United Nations. Single convention on narcotic drugs, 1961. New York, 30 March 1961. United Nations Treaty Series 1961; 520: 151.

5. United Nations. Convention on Psychotropic Substances, 1971. Vienna, 21 February 1971. United Nations Treaty Series 1971; 1019: 175.

6. Santhireswaran A, Chaudhry S, Ho M, Fuller K, Gaudette E, Burry L, et al. Impact of supply chain disruptions and drug shortages on drug utilization: A scoping review. Pharmacoepidemiol Drug Saf. 2025; 34: e70178.

7. U.S. Food and Drug Administration. Drug shortages: root causes and potential solutions [online]. 2019 [cited Nov 10, 2025]. Available from: www.fda.gov/media/132058/download

8. Mak S, Thomas A. Steps for conducting a scoping review. J Grad Med Educ. 2022; 14: 565-7.

9. Arksey H, O'Malley L. Scoping studies: towards a methodological framework. Int J Soc Res Methodol 2005; 8: 19-32.

10. Hadie SNH. ABC of a scoping review: a simplified JBI scoping review guideline. Educ Med J. 2024; 16: 185-97.

11. Levac D, Colquhoun H, O'Brien KK. Scoping studies: advancing the methodology. Implement Sci. 2010; 5: 69.

12. Peters MDJ, Godfrey CM, Khalil H, McInerney P, Parker D, Soares CB. Guidance for the conduct of JBI scoping reviews. In: Aromataris E, Munn Z, editors. Joanna Briggs Institute Reviewer's Manual. Adelaide: The Joanna Briggs Institute; 2017. Chapter 11.

13. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021; 372: n71.

14. Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation. Ann Intern Med. 2018; 169: 467-73.

15. Rahman MS, Nahar N, Imam MH, Bhuyian MN, Rahman MA, Khandaker MU, et al. A blockchain-based framework for drug security: Leveraging EdDSA to prevent counterfeiting. Array. 2025; 28: 100604.

16. Pham HL, Tran TH, Nakashima Y. Practical anti-counterfeit medicine management system based on blockchain technology. In: 2019 4th Technology Innovation Management and Engineering Science International Conference (TIMES-iCON); 2019; Bangkok, Thailand. p. 1-5. doi: 10.1109/TIMES-iCON47539.2019.9024674.

17. Ahmadi V, Benjelloun S, El Kik M, Sharma T, et al. Drug governance: IoT-based blockchain implementation in the pharmaceutical supply chain. In: Proceedings of the 6th International Conference on Mobile and Secure Services (MobiSecServ 2020); 2020. doi:10.1109/MobiSecServ48690.2020.9042950

18. Saindane P, Jethani Y, Mahtani P, Rohra C, Lund P. Blockchain: A solution for improved traceability with reduced counterfeits in supply chain of drugs. In: Proceedings of the 2020 International Conference on Electrotechnical Complexes and Systems (ICOECS); 2020 Oct 27–30; Ufa, Russia. IEEE. doi:10.1109/ICOECS50468.2020.9278412

19. Musamih A, Salah K, Jayaraman R, Arshad J, Debe M, Al-Hammadi Y, et al. A blockchain-based approach for drug traceability in healthcare supply chain. IEEE Access. 2021; 9: 9728-43.

20. Akram W, Joshi R, Haider T, Sharma P, Jain V, Garud N, et al. Blockchain technology: A potential tool for the management of pharma supply chain. Res Social Adm Pharm. 2024; 20: 156-64.

21. Humayun M, Jhanjhi N, Niazi M, Amsaad F, Masood I. Securing drug distribution systems from tampering using blockchain. Electronics. 2022; 11: 1195.

22. Abdallah S, Nizamuddin N. Blockchain-based solution for pharma supply chain industry. Comput Ind Eng. 2023; 177: 108997.

23. Gaynor M, Gillespie K, Roe A, Crannage E, Tuttle-Newhall JE. Blockchain applications in the pharmaceutical industry. Blockchain Healthc Today. 2024; 7. doi: 10.30953/bhty.v7.298.

24. Shanthi P, Venkatesh K. Blockchain assisted Archimedes optimization with machine learning driven drug supply management for pharmaceutical sector. In: Proceedings of the 2023 International Conference on Advances in Computing, Communication and Applied Informatics (ACCAI); 2023 May 25–26; Chennai, India. IEEE; 2023. doi:10.1109/ACCAI58221.2023.10199884.

25. Crossland V, Dellwo C, Bashar GD, Dagher GG. Janus: toward preventing counterfeits in supply chains utilizing a multi-quorum blockchain. Blockchain Res Appl. 2023; 4: 100157. doi:10.1016/j.bcra.2023.100157.

26. Nanda, S.K., Panda, S.K. & Dash, M. Medical supply chain integrated with blockchain and IoT to track the logistics of medical products. Multimed Tools Appl 82, 32917–32939 (2023). doi.org/10.1007/s11042-023-14846-8

27. Shah K, Rana S, Solanki N, Desai V, Prajapati D, Vasita U. Blockchain-based pharmaceutical drug supply chain management system. In: Proceedings of the 2022 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME); 2022 Nov 16–18; Maldives. IEEE; 2022. doi:10.1109/ICECCME55909.2022.9987875.

28. Bapatla AK, Mohanty SP, Kougianos E, Puthal D. PharmaChain 3.0: blockchain integrated efficient QR code mechanism for pharmaceutical supply chain. In: Proceedings of the 2022 OITS International Conference on Information Technology (OCIT); 2022 Dec 14–16; Bhubaneswar, India. IEEE; 2022. doi:10.1109/OCIT56763.2022.00121.

29. Kumar D, Kumar D. Modelling rural healthcare supply chain in india using system dynamics. Procedia Eng. 2014; 97: 2204-12.

30. Wu D, Rossetti MD, Tepper JE. Possibility of inventory pooling in china's public hospital and appraisal about its performance. Appl Math Model. 2015; 39: 7277-90.

31. Kumar D, Kumar D. SD modelling of healthcare supply chain in rural parts of Uttarakhand, India. In: Proceedings of the 2015 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM); 2015 Dec 6–9; Singapore. IEEE; 2015. doi:10.1109/IEEM.2015.7385657.

32. Bam L, McLaren ZM, Coetzee E, von Leipzig KH. Reducing stock-outs of essential tuberculosis medicines: a system dynamics modelling approach to supply chain management. Health Policy Plan. 2017; 32: 1127-34.

33. Gonul Kochan C, Nowicki DR, Sauser B, Randall WS. Impact of cloud-based information sharing on hospital supply chain performance: a system dynamics framework. Int J Prod Econ. 2018; 195: 168-85

34. Jenzer H, Maag P, Groesser SN. 2SPD-048 political report—options to break through medicine shortages. Eur J Hosp Pharm. 2021;28(Suppl 1): A15. doi:10.1136/ejhpharm-2021-eahpconf.31.

35. Kant S, Haldar P, Singh A, Kankaria A. Inventory management of drugs at a secondary level hospital associated with ballabgarh HDSS- an experience from north India. J Young Pharm. 2015; 7: 113-7.

36. Guru RR, Mitra S, Jadhav SJ, Maikano AK, Kumar R. Buffer stock inventory control mechanism: An approach of minimizing the buffer stock level through segmentation at a tertiary care rural hospital. Cureus. 2024; 16: e67423.

37. Mfizi E, Niragire F, Bizimana T, Mukanyangezi MF. Analysis of pharmaceutical inventory management based on ABC-VEN analysis in Rwanda: a case study of Nyamagabe district. J Pharm Policy Pract. 2023; 16: 30

38. Lotfi R, MohajerAnsari P, Sharifi Nevisi MM, Afshar M, Reza Davoodi SM, Ali SS. A viable supply chain by considering vendor-managed-inventory with a consignment stock policy and learning approach. Results Eng. 2024; 21: 101609.

39. Tucker EL. Modeling pharmaceutical supply chains to mitigate drug shortages [dissertation]. Ann Arbor (MI): University of Michigan; 2020.

40. Choi JB, Rogers J, Jones EC. The impact of a shared pharmaceutical supply chain model on counterfeit drugs, diverted drugs, and drug shortages. In: Proceedings of the 2015 Portland International Conference on Management of Engineering and Technology (PICMET); 2015 Aug 2–6; Portland, OR, USA. IEEE; 2015. doi:10.1109/PICMET.2015.7273165.

41. Jaju R, Varshney S, Gupta P, Bihani P, Karim HMR. Inventory Control Mechanism of the Pharmacy Store of a Recently Established National Institute in Eastern India: A Cross-Sectional, Investigative Analysis. Cureus. 2023; 15: e49632

42. King B, Zhang X. Securing the pharmaceutical supply chain using RFID. In: Proceedings of the 2007 International Conference on Multimedia and Ubiquitous Engineering (MUE'07); 2007 Apr 26–28; Seoul, South Korea. IEEE; 2007. doi:10.1109/MUE.2007.186.

43. Eapen AT. The science of supply: applying diffusion models to predict and prevent drug shortages [dissertation]. Washington (DC): George Washington University; 2024.