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Energy-Aware and AI-Driven IoT Solutions for Sustainable Pharmaceutical Supply Chains: A Review of Cold-Chain Optimization and Digital Technologies

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Abstract

The pharmaceutical supply chain is a critical and energy-intensive network, particularly due to temperature-sensitive products requiring continuous refrigeration. Ensuring product quality and safety while minimizing energy consumption has become an essential challenge. Despite growing interest in digital technologies for pharmaceutical logistics, a structured synthesis of AI-driven energy optimization and IoT-enabled sustainability in cold chains remains lacking. This review systematically analyzes the application of the Internet of Things (IoT), Artificial Intelligence (AI), and complementary digital technologies in enhancing energy efficiency, operational performance, and sustainability of pharmaceutical cold chains. A total of 76 peer-reviewed studies—including empirical investigations, case studies, architecture proposals, optimization frameworks, and conceptual models—were examined to identify technological trends, methodological approaches, and practical outcomes. Findings highlight how IoT-enabled sensors, Radio Frequency Identification (RFID) systems, and cloud-based platforms facilitate real-time monitoring, intelligent inventory management, and predictive decision-making. Integration with AI supports demand forecasting, anomaly detection, and energy-aware cold-chain optimization, while blockchain ensures secure, traceable, and tamper-resistant recording of events. Results indicate that digital solutions can reduce energy consumption, minimize waste, improve regulatory compliance, and enhance operational resilience. Challenges such as cybersecurity, standardization gaps, high implementation costs, and organizational barriers remain critical considerations. By synthesizing technological innovations, operational strategies, and sustainability implications, this review provides a structured roadmap for AI- and IoT-enabled energy-efficient supply chain management, offering actionable guidance for researchers, policymakers, and industry practitioners seeking sustainable and smart pharmaceutical logistics solutions.

Keywords: Energy-Efficient Supply Chain; Internet of Things; Artificial Intelligence; Cold-Chain Logistics; Blockchain; RFID; Sustainable Operations; Predictive Analytics.

1. Introduction

The pharmaceutical supply chain is a complex and multi-layered system encompassing raw material procurement, manufacturing, packaging, warehousing, distribution, and final delivery to patients. Failures in monitoring and coordination at any stage can directly affect product quality, safety, and therapeutic effectiveness. This complexity becomes even more critical in cold-chain logistics, where temperature-sensitive medicines such as vaccines, biologics, and insulin require continuous refrigeration and strict environmental control. Such requirements make pharmaceutical logistics not only a safety-critical sector, but also an energy-intensive supply chain in which electricity consumption, refrigeration efficiency, and sustainable transportation practices play a significant role in operational performance. Many pharmaceutical products are highly sensitive to environmental conditions such as temperature, humidity, and light; even minor deviations can lead to product degradation, increased waste, economic losses, and serious risks to patient health due to rework, emergency transportation, and disposal. Therefore, improving transparency and real-time monitoring is essential for regulatory compliance, reducing energy waste, and supporting sustainability goals. The pharmaceutical supply chain involves a wide range of stakeholders—including manufacturers, raw material suppliers, packaging firms, warehouses, logistics providers, distributors, pharmacies, and healthcare institutions. This stakeholder diversity, combined with the geographical dispersion of distribution networks, particularly in cross-border trade, introduces major challenges related to coordination, interoperability, and real-time information sharing. Lack of traceability may delay the detection of disruptions, increase operational costs, and reduce responsiveness to demand fluctuations and crisis conditions.

Traditional supply chain management approaches relying on manual documentation and paper-based records cannot provide real-time monitoring, integrated decision support, or reliable traceability. Meanwhile, the growing threat of counterfeit and tampered medicines undermines trust in healthcare systems, demanding digital mechanisms that guarantee transparency, secure data sharing, and immutable recording of events to ensure authenticity and track the origin of each pharmaceutical unit. In addition, demand uncertainty, short-term shortages, and limited shelf-life constraints necessitate advanced forecasting, rapid response capabilities, and energy-aware cold-chain capacity planning. The Internet of Things (IoT) provides a cyber-physical infrastructure through networks of connected sensors, Radio Frequency Identification (RFID) tags, and smart devices that continuously collect, transmit, and process real-time data on temperature, humidity, shock, and location throughout the distribution process. Such real-time visibility enables early warning mechanisms, logistics optimization, risk mitigation, and energy-efficient cold-chain management. The integration of IoT with complementary technologies, particularly blockchain and artificial intelligence (AI), further extends these capabilities. Blockchain enables secure and tamper-resistant recording of transactions, improving traceability and reducing counterfeit risks. AI and machine learning, supported by big data generated through IoT devices, facilitate demand forecasting, anomaly detection, predictive maintenance of cold-chain equipment, and intelligent routing decisions. Moreover, a growing body of research has begun to apply AI-driven optimization—including reinforcement learning and deep learning—directly to energy management in cold-chain logistics, enabling dynamic temperature control, energy-aware route planning, and multi-objective trade-offs between cost, quality, and environmental impact. These capabilities contribute not only to safety and efficiency, but also to sustainability by reducing spoilage, minimizing unnecessary transportation, and optimizing energy consumption in refrigerated storage and distribution systems. Despite the promising potential of IoT-driven digital transformation, several barriers remain. Cybersecurity and data privacy are major concerns, as supply chain data may include sensitive operational information and, in some cases, patient-related records. Furthermore, the lack of unified standards and interoperable protocols increases integration complexity and limits scalability across different supply chain actors. High initial investment costs, the need for reliable communication infrastructure, and organizational resistance to change are additional challenges that affect adoption.

To achieve effective and sustainable implementation, a multidimensional approach is required, including secure and scalable architectures (edge, fog, and cloud-based frameworks), standardized governance and interoperability protocols, sustainable business models, pilot implementations with cost–benefit evaluation, and clear regulatory frameworks for data and operational accountability. Future research should move beyond conceptual demonstrations and focus on quantifying operational, economic, and sustainability impacts through comparative evaluations of technical architectures, energy-aware optimization models, carbon footprint assessment, and policy-oriented analyses. Ultimately, the adoption of IoT, AI, and blockchain technologies aims to enhance patient access to safe and authentic medicines while simultaneously reducing waste, improving energy efficiency, and supporting sustainable supply chain management. The main objectives of this review are: (i) to systematically analyze the impact of IoT, RFID, blockchain, and AI technologies on security, authenticity, and performance in pharmaceutical supply chains; (ii) to examine the synergy of these technologies and compare alternative architecture paradigms (edge-based, cloud-based, and distributed-ledger-integrated systems) in terms of scalability, cybersecurity, and implementation cost; (iii) to identify energy and sustainability-related implications, including waste reduction and AI-driven energy-efficient cold-chain logistics; and (iv) to provide structured recommendations for policymakers and industry stakeholders regarding standardization, governance frameworks, training programs, and scalable deployment strategies.

This paper is organized as follows. Section 2 details the systematic review methodology. Section 3 presents the thematic literature review across seven research domains. Section 4 analyzes publication trends, technology distribution, and methodological patterns. Section 5 discusses practical implications and recommendations. Section 6 concludes with key insights and future directions.

2. Methodology

A systematic literature review approach was adopted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to ensure transparency, reproducibility, and methodological rigor. The review protocol encompassed four phases: identification, screening, eligibility assessment, and inclusion, as detailed below.

2-1. Research Questions and Search Strategy

The review was guided by the following research questions:

- *RQ1:* How do IoT, RFID, blockchain, and AI technologies enhance security, authenticity, and operational performance in pharmaceutical supply chains?
- *RQ2:* What are the synergies among these technologies, and how do alternative architectural paradigms compare in terms of scalability, cybersecurity, and implementation cost?
- *RQ3:* What are the energy and sustainability implications of digital technologies in pharmaceutical cold-chain logistics?
- *RQ4:* What are the key barriers, governance challenges, and research gaps limiting large-scale adoption?

A structured literature search was conducted in Scopus, Web of Science, and PubMed, selected for their comprehensive coverage of engineering, computer science, and health sciences literature. The search was performed in January 2025 and updated through February 2026 to capture the most recent publications. The Boolean search strategy combined terms from four thematic clusters, as detailed in Table 1.

The search was applied to titles, abstracts, and keywords. No language restrictions were imposed. The search was supplemented by backward citation tracking (snowballing) from highly cited and domain-relevant publications, as well as forward citation tracking through Google Scholar.

2-2. Inclusion and Exclusion Criteria

Studies were selected based on the predefined inclusion and exclusion criteria summarized in Table 2.

2-3. Screening Process and Study Selection

The screening process followed the PRISMA 2020 three-stage approach of identification, screening, and eligibility assessment, as described below.

Stage 1) *Identification:* The initial database search across Scopus, Web of Science, and PubMed, combined with supplementary records identified through backward and forward citation tracking of highly cited and domain-relevant publications, yielded a combined initial pool of records. After removing duplicate records using reference management software (EndNote) and manual verification, unique records proceeded to the title and abstract screening stage.

Table 1. Thematic clusters and Boolean search terms used in the systematic review

Theme	Search terms
Technology	"Internet of Things" OR "IoT" OR "RFID" OR "blockchain" OR "distributed ledger" OR "artificial intelligence" OR "machine learning" OR "deep learning" OR "reinforcement learning"
Supply chain	"supply chain" OR "logistics" OR "cold chain" OR "cold-chain"
Domain	"pharmaceutical" OR "pharma" OR "drug" OR "medicine" OR "vaccine" OR "biologics"
Performance	"energy" OR "energy-aware" OR "energy-efficient" OR "sustainability" OR "optimization" OR "traceability" OR "monitoring" OR "transparency"

Table 2. Inclusion and exclusion criteria for study selection.

Inclusion Criteria	Exclusion Criteria:
• (IC1) Peer-reviewed journal articles, conference proceedings, and book chapters; • (IC2) Studies directly addressing IoT, RFID, blockchain, or AI applications in pharmaceutical supply chain management, cold-chain logistics, or related healthcare logistics domains; • (IC3) Empirical investigations (quantitative, qualitative, or mixed methods), case studies, architecture proposals, optimization frameworks, or conceptual models with clear implementation implications; • (IC4) Publications in English; • (IC5) Publication timeframe: 2003–2025 (early RFID and IoT foundational works were retained to illustrate the evolution of the field).	• (EC1) Studies focused exclusively on clinical applications of IoT or AI without supply chain relevance; • (EC2) Articles addressing general supply chain management without pharmaceutical or healthcare logistics context; • (EC3) Editorials, commentaries, news articles, and non-peer-reviewed white papers; • (EC4) Duplicate publications or studies reporting identical data across multiple outlets.

Stage 2) *Screening:* The titles and abstracts of all unique records were independently screened by two reviewers against the predefined inclusion and exclusion criteria (Section 2.2). Records that were clearly irrelevant to the research scope—such as studies focused exclusively on clinical applications without supply chain relevance or general logistics without a pharmaceutical context—were excluded at this stage. The remaining records were retained for full-text retrieval.

Stage 3) *Eligibility:* The full texts of all records that passed the title and abstract screening were retrieved and independently assessed by two reviewers against the complete set of inclusion and exclusion criteria. The primary reasons for exclusion at this stage were: (*i*) no substantive focus on pharmaceutical supply chain management; (*ii*) insufficient technical detail on digital technology implementation; (*iii*) purely conceptual essays without methodological grounding; and (*iv*) unavailability of the full text despite attempted retrieval through institutional access and interlibrary loan. Disagreements between the two reviewers at any stage were resolved through consensus discussion; where consensus could not be reached, a third reviewer was consulted to arbitrate.

After the completion of all screening stages, a final set of 76 studies was deemed eligible and was included in the qualitative and thematic synthesis.

2-4. Data Extraction and Synthesis

From each included study, the following data elements were extracted: (*i*) bibliographic information (authors, year, journal/conference); (*ii*) research focus and objectives; (*iii*) technologies examined (IoT, RFID, blockchain, AI/ML); (*iv*) research methodology (qualitative, quantitative, mixed methods); (*v*) type of contribution (empirical, case study, architecture, optimization model, conceptual framework); (*vi*) domain of application within the pharmaceutical supply chain (traceability, cold-chain monitoring, demand forecasting, architecture design, cybersecurity/governance); (*vii*) key findings and reported outcomes; and (*viii*) limitations noted by the original authors. Extracted data were synthesized using thematic analysis. Studies were categorized into seven thematic domains based on recurring themes identified through content analysis of paper objectives and contributions: (*i*) transparency and traceability, (*ii*) cold-chain environmental monitoring and quality assurance, (*iii*) AI-driven energy optimization models for cold chains, (*iv*) demand forecasting, inventory optimization, and machine learning, (*v*) architectures, conceptual models, and cyber-physical system design, and (*vi*) cybersecurity, protocol design, and technology governance. Systematic reviews and integrative frameworks formed an additional category. This classification structure is presented in detail in Section 3.

2-5. Summary of Included Studies

Table 3 provides a summary overview of the key characteristics of the 76 included studies, categorized by thematic domain, technology focus, and methodological approach.

3. Literature Review

In this section, the selected studies were systematically categorized according to their research focus and methodological approach in order to highlight the dominant research streams and identify knowledge gaps. Based on recurring themes extracted through content analysis of paper objectives and contributions, the literature was classified into seven main domains: (i) transparency and traceability, (ii) cold-chain environmental monitoring and quality assurance, (iii) AI-driven energy optimization models for cold chains, (iv) demand forecasting and inventory management, (v) technical architectures and conceptual frameworks, (vi) cybersecurity, governance, and regulatory compliance, and (vii) systematic reviews and integrative frameworks.

Table 3. Summary characteristics of included studies (n = 76)

Thematic Domain	No.	Primary Technologies	Dominant Research Method
Transparency and Traceability	27	Blockchain, RFID, IoT–Blockchain	Qualitative, Architecture design
Cold-Chain Monitoring & Quality Assurance	5	IoT, RFID, Blockchain	Quantitative, Experimental/Case study
AI-Driven Energy Optimization	7	AI/ML, IoT, Reinforcement Learning	Quantitative, Optimization modeling
Demand Forecasting & Inventory Management	6	Machine Learning, IoT	Quantitative, Predictive modeling
Architectures, CPS Design & Digital Twins	20	IoT, Blockchain, Edge/Cloud, Digital Twin	Conceptual framework, Architecture proposal
Cybersecurity, Governance & Compliance	5	RFID security, Blockchain governance	Qualitative, Protocol design
Systematic Reviews & Integrative Frameworks	6	All technologies	Systematic review, Meta-synthesis

This classification enables a coherent mapping of both enabling technologies (e.g., RFID, IoT platforms, blockchain, and machine learning) and operational challenges (e.g., product integrity, demand volatility, governance, and sustainable deployment).

The references were identified through structured searches in major scientific databases and conference proceedings, complemented by backward citation tracking from highly cited and domain-relevant publications. Studies were included if they directly addressed IoT-enabled or digitally enhanced pharmaceutical supply chain management, with emphasis on traceability, safety, efficiency, or sustainability-related outcomes. A broad range of research designs was considered, including empirical investigations, case studies, architecture proposals, optimization frameworks, and conceptual models. Studies with limited relevance to pharmaceutical logistics or without clear implementation implications were excluded in order to maintain an evidence-driven and practice-oriented review scope.

3-1. Transparency and Traceability

Research on transparency and traceability primarily investigates the role of distributed ledger technologies and automated identification systems in preventing counterfeiting and improving supply chain accountability. Abbas et al. (2020) proposed a blockchain- and machine learning-based framework to enhance transparency and recommendation services, while Bocek et al. (2017) demonstrated through a case study that distributed ledgers can strengthen transaction recording reliability. In parallel, RFID-oriented studies examined operational feasibility, technical constraints, and deployment risks. Acierno et al. (2011) evaluated technological aspects and risk factors of RFID-based tracking systems, whereas Chang et al. (2012) tested RFID-based positioning in automated packaging to improve packaging accuracy and reduce operational errors. In addition, hybrid research streams proposed integrated IoT–blockchain infrastructures to enable end-to-end provenance tracking. Botcha et al. (2019) discussed implementation strategies for IoT–blockchain integration, and Bryatov and Borodinov (2019) investigated operational deployment through Hyperledger-based business platforms. Overall, this line of research indicates that blockchain-supported traceability can significantly improve trust, auditability, and counterfeit prevention; however, scalability and cost remain major challenges, especially for high-volume pharmaceutical distribution networks.

A broader body of work has examined RFID adoption drivers and barriers. Angeles (2012) applied the TOE framework to a case study of Purdue Pharma, identifying organizational and technological factors influencing RFID adoption. Haji et al. (2021) synthesized critical success factors and traceability technologies, offering a multi-dimensional evaluation of operational, regulatory, and strategic dimensions essential for a safe pharmaceutical supply chain. Blockchain-based anti-counterfeiting solutions have been further explored by Bansal et al. (2013), who provided a comprehensive overview of anti-counterfeit technologies from an industry perspective, and by Trautmann et al. (2024), who proposed a blockchain concept specifically designed to combat drug counterfeiting by increasing supply chain visibility. Sylim et al. (2018) investigated the use of blockchain for detecting falsified and substandard drugs in distribution, outlining a pharmaceutical supply chain intervention protocol. Aziz et al. (2025) leveraged blockchain for combating drug counterfeiting, while Kutybayeva et al. (2025) integrated blockchain with big data to enhance supply chain transparency and security.

Hybrid IoT–blockchain models for traceability and transparency have also been advanced. D'souza et al. (2021) explored the combined use of blockchain and AI in pharmaceutical supply chains, and Premkumar and Srimathi (2020) demonstrated applications of blockchain and IoT toward the pharmaceutical industry. Kumar and Tripathi (2019) proposed a blockchain-based traceability system specifically for counterfeit medicine supply chains. Kumar and Pundir (2020) developed a blockchain–IoT enabled pharmaceutical supply chain framework tailored for COVID-19 response. Rejeb et al. (2019) provided a broader perspective on leveraging IoT and blockchain in supply chain management, outlining benefits in transparency, traceability, and operational efficiency. Sarkar (2022) reviewed digital traceability mechanisms for pharmaceutical drugs, while Shashi and Gossett (2022) explored strategies for leveraging blockchain in pharmaceutical supply chains. Further hybrid frameworks have been proposed. Chen et al. (2023) investigated IoT–blockchain-enabled pharmaceutical supply chain resilience in the post-pandemic era, demonstrating how combined digital technologies can enhance disruption preparedness and recovery. Alangot and Achuthan (2018) presented a "Trace and Track" framework to prevent fraud through enhanced pharma supply chain infrastructure. Jangir et al. (2021) developed a novel framework based on distributed ledger technology and smart contracts for pharmaceutical supply chain management. Jayaraman et al. (2019) explored opportunities for improving healthcare supply chain processes through IoT and blockchain integration. In a related healthcare context, Pham et al. (2023) designed a blockchain-based electronic health record system using Hyperledger Fabric, demonstrating the broader applicability of distributed ledger technologies beyond drug traceability to patient data security.

In addition to general-purpose traceability frameworks, recent research has begun to tailor blockchain-based solutions specifically to cold-chain pharmaceutical logistics. Ramkumar et al. (2024) proposed a Deep Learning-based Cold-Chain Distribution Model (DL-CCDM) that integrates blockchain, cloud storage, and IoT to ensure end-to-end traceability of pharmaceutical products throughout their lifecycle, embedding smart contracts to automate quality assurance verification and tamper-resistant event logging. Yadav et al. (2025) proposed a data-driven, scenario-based blockchain framework that leverages smart contracts to ensure drug authenticity and traceability while preserving privacy. The framework's feasibility was demonstrated through rigorous cost and security analyses. These studies collectively illustrate the evolution of traceability solutions from generic supply chain visibility toward domain-specific, cold-chain-aware architectures that simultaneously address product integrity, regulatory compliance, and operational efficiency.

3-2. Energy-Aware IoT Systems

Cold-chain monitoring has received significant attention due to the safety-critical nature of temperature-sensitive pharmaceuticals such as vaccines and biologics. Beyond product integrity, this domain is increasingly linked to sustainability and energy efficiency, as refrigerated warehousing and transportation impose high energy demands and contribute to the overall carbon footprint of healthcare logistics.

The reviewed studies demonstrate that IoT-based sensing, anomaly detection algorithms, and blockchain-enabled data integrity mechanisms can improve monitoring reliability and reduce losses due to temperature excursions. Singh et al. (2020) proposed an IoT–blockchain solution for temperature monitoring and counterfeit prevention, while Chen et al. (2017) developed an RFID anomaly detection framework to validate monitoring data. At the supply network design level, Goodarzian et al. (2023) introduced a responsive and green vaccine cold-chain model integrating IoT and AI to improve service level and sustainability performance. Konovalenko and Ludwig (2021) compared machine learning classifiers for temperature alarm systems to improve anomaly detection accuracy and reduce false positives, which is critical for energy-efficient decision-making and minimizing unnecessary interventions.

Although not directly focused on energy optimization, several studies have explored IoT-driven improvements in pharmaceutical supply chain performance that indirectly contribute to operational efficiency and waste reduction. Bakhsham et al. (2023) identified and analyzed key IoT applications for enhancing agility in post-COVID pharmaceutical supply chains, highlighting how IoT-enabled visibility can reduce energy waste by enabling more responsive and streamlined logistics. Empirical evidence further suggests that hardware limitations, such as RFID tag readability constraints, can influence the feasibility of item-level monitoring and must be considered in system design. Erdem et al. (2009) experimentally assessed RFID readability at the pharmaceutical item level, highlighting the importance of physical infrastructure reliability in real-world deployments.

Beyond anomaly detection and temperature monitoring, recent studies have introduced automated optimization frameworks for energy-sensitive pharmaceutical cold storage. Montes et al. (2024) addressed the research gap in mathematical procedures for automatic control of energy-sensitive industrial processes by applying IoT-enabled control charts to refrigerated pharmaceutical warehouses. Their approach enables real-time detection of energy inefficiencies and automated adjustment of refrigeration parameters, reducing energy consumption without compromising product safety. In a related line of research, Ramasamy and Pravinkumar (2023) devised an RL-based feedback mechanism for cold storage temperature control.

3-3. AI-Driven Energy Optimization Models for Cold Chains

Complementing monitoring and traceability, a distinct and rapidly growing research stream has emerged around AI-driven energy optimization models explicitly designed for pharmaceutical cold-chain logistics. While IoT and blockchain provide the data infrastructure and trust layer, AI algorithms are increasingly employed as the analytical engine to achieve measurable energy savings, reduce carbon footprint, and optimize operational efficiency. Goodarzian et al. (2023) formulated an integrated responsive-green-cold vaccine supply chain network model that leverages IoT and AI-based solution approaches, simultaneously optimizing service levels, environmental impact, and energy consumption. Their model demonstrates that multi-objective optimization can reconcile sustainability goals with operational performance in cold-chain network design. Similarly, Leng et al. (2024) developed a comprehensive energy-conserving cold-chain distribution model that incorporates ambient temperature variability, flexible paths, and hybrid fleet composition. By applying Q-learning—a reinforcement learning algorithm—their model enables a multi-dimensional trade-off among cost, product quality, delivery timeliness, and environmental impact, offering a holistic optimization framework for energy-aware logistics decision-making.

From a real-time control perspective, IoT-enabled reinforcement learning has been applied directly to refrigerated transport and storage. Ramasamy and Pravinkumar (2023) devised an RL-based feedback mechanism to continuously measure, monitor, and correct the temperature of cold storage units for temperature-sensitive vaccines such as Lupride and Degapride. Their work illustrates that extending the state definition of the RL agent with meaningful operational variables is key to achieving high accuracy in optimal cooling energy dosing. In a similar context, Kavididevi et al. (2024) introduced an IoT-enabled RL framework that integrates real-time sensor data with decision agents to dynamically optimize temperature and humidity control during refrigerated transport. Their simulation-based assessment demonstrated significant reductions in spoilage rates and energy consumption compared to conventional rule-based control strategies. In addition to operational optimization, AI-driven anomaly detection contributes to energy efficiency by minimizing unnecessary interventions and preventing energy-intensive temperature excursions. Konovalenko and Ludwig (2021) compared multiple machine learning classifiers for temperature alarm systems, demonstrating that improved anomaly detection accuracy directly reduces false positives and, consequently, the energy wasted on unnecessary corrective actions. On a broader scale, integrative frameworks have begun to articulate the convergence of AI, big data, and energy-aware IoT as a unified paradigm for cold-chain optimization. Sheng et al. (2026) proposed an AI-driven big data acquisition and optimization framework that integrates energy-aware IoT systems with advanced analytics, achieving reported energy consumption reductions of up to 35% and emission reductions of 25% in cold-chain logistics applications. Beyond cold-chain-specific applications, AI-driven optimization models in broader healthcare supply chain contexts offer relevant insights for energy-aware logistics. Zavvar Sabegh et al. (2017) proposed a multi-objective optimization model considering quality concepts in a green healthcare supply chain for natural disaster response, employing neural network approaches. Their model addresses the trade-off between cost, quality, and environmental sustainability, demonstrating the adaptability of AI optimization to healthcare logistics challenges with energy and environmental implications.

Collectively, these studies establish AI-driven energy optimization as a critical pillar of sustainable pharmaceutical supply chains. The research trajectory indicates a shift from passive monitoring toward active, AI-enabled energy management—ranging from strategic network design and vehicle routing to real-time refrigeration control. Future research in this domain should focus on developing lightweight, interpretable AI models suitable for edge deployment in resource-constrained cold-chain environments, as well as on standardizing energy performance metrics to enable cross-study comparisons.

3-4. Demand Forecasting, Inventory Optimization, and Machine Learning

Demand forecasting and inventory management represent another key research stream, particularly due to demand volatility and the high cost of shortages for essential medicines. Studies consistently show that combining IoT-generated operational data with machine learning models can improve forecasting accuracy and enable data-driven inventory policies. Dutta et al. (2022) applied machine learning algorithms to detect complex sales patterns and risk-related variables, while Mbonyinshuti et al. (2022) developed predictive models for essential medicine demand using consumption datasets. Zhou et al. (2021) further demonstrated that integrating supply chain information into machine learning-based forecasting frameworks significantly enhances predictive performance. In addition, Bahaghighat et al. (2019) proposed machine learning-based automation for blister card counting, contributing to improved inventory control accuracy and reduced manual workload. Complementing these efforts, Gobinath et al. (2024) employed machine learning intelligence to improve supply chain management in e-pharmacy, demonstrating enhanced demand prediction and inventory optimization in a digital pharmacy setting. Pazhayattil and Konyu-Fogel (2023) provided practical insights into implementing machine learning and AI in biopharma manufacturing, highlighting operational considerations and data readiness factors critical for successful adoption. Extending beyond traditional demand forecasting, recent contributions have applied reinforcement learning to operational decision-making in cold-chain logistics. Kavididevi et al. (2024) introduced an IoT-enabled reinforcement learning framework that integrates real-time sensor data with RL-based decision agents to dynamically optimize temperature and humidity control during refrigerated transport, demonstrating significant reductions in spoilage rates and energy consumption compared to conventional rule-based control strategies. Beyond operational control, AI-driven optimization models have also been applied to reduce energy consumption and emissions in cold-chain distribution. For instance, Leng et al. (2024) developed an energy-conserving cold-chain model using Q-learning to balance cost, quality, and environmental objectives.

This literature suggests that AI-driven forecasting can reduce waste from overstocking, minimize emergency shipments, and indirectly contribute to energy efficiency and sustainability through optimized warehousing and transportation planning.

3-5. Architectures, Conceptual Models, and Cyber-Physical System Design

A substantial portion of the literature focuses on developing architectures and conceptual frameworks to support scalable IoT deployment in pharmaceutical supply chains. Kangarloo Haghighi et al. (2021) proposed an agent-based conceptual model for online monitoring, providing a theoretical foundation for intelligent tracking systems. Liu and Jia (2010) introduced an IoT-based business model to explain value creation in pharmaceutical logistics, while Ouf (2021) proposed a semantic blockchain architecture enabling integration of distributed ledger technologies with semantic interoperability. Furthermore, Liu et al. (2021) designed a blockchain-based intelligent tracking platform, and Schapranow et al. (2011) introduced a formal model for RFID activation. Collectively, these studies highlight that cyber-physical architectures integrating edge computing, cloud platforms, and distributed ledgers are critical for enabling real-time decision support and scalable digital transformation. Additional studies have contributed to the design of IoT-enabled architectures and conceptual models. Abadi et al. (2023) developed a smart supply chain management model using fuzzy cognitive maps under IoT technology, providing a decision-support framework for complex pharmaceutical logistics. Rehdar et al. (2023) examined how IoT can be employed to improve efficiency and accuracy in pharmaceutical supply chains, offering practical implementation perspectives.

Early foundational works on IoT and RFID information architectures include Yan and Huang (2009), who modeled supply chain information transmission based on RFID and IoT, and Wahlster (2013), who edited a comprehensive volume on semantic product memories for the Internet of Things, establishing conceptual groundwork for intelligent product tracking. Several studies have focused on IoT adoption and risk management. Angeles (2012), also cited in Section 3.1, used the TOE framework to analyze RFID adoption; Montoya et al. (2018) applied IoT to risk management in pharmaceutical supply chains, developing a conceptual approach for identifying and mitigating disruptions. Merlino et al. (2017) explored the adoption of new technologies, including IoT, in enhanced supply chain management through an operations management lens. Marathe and Awwad (2018) reviewed IoT opportunities and applications in pharmaceutical manufacturing and logistics, highlighting the potential for real-time asset tracking and condition monitoring.

Smart logistics and manufacturing studies have further enriched the architectural discourse. Pachayappan et al. (2016) proposed a smart logistics model for the pharmaceutical industry based on IoT, while Sharma et al. (2020) comprehensively reviewed IoT applications in pharmaceutical manufacturing, warehousing, and supply chain management. Jyothy and Sarvagya (2022) presented an IoT-based supply chain management framework for the pharmaceutical industry, and Kumar (2023) discussed the optimization of pharmaceutical supply chains using digital technologies. Finally, Singh et al. (2020) reviewed the broader landscape of IoT applications to fight against the COVID-19 pandemic, including supply chain implications, and Mishra et al. (2020) catalogued applications of IoT in the pharmaceutical industry, covering manufacturing, logistics, and quality assurance aspects.

Moving beyond traditional cloud-centric and edge-based frameworks, the Digital Twin (DT) concept has recently been explored as an emerging architectural paradigm for pharmaceutical cold-chain quality improvement. Sun and Wang (2025) applied multi-source data integration to cold-chain logistics through a digital twin framework, demonstrating that digital twins can significantly improve operational performance by enhancing visibility and providing predictive insights. From a practical deployment perspective, Alshdadi et al. (2024) designed and implemented a complete IoT smart system for cold supply chain storage and transportation management. Their global monitoring framework connects to a cloud-storage platform continuously accessible by all supply chain parties—including the provider, transporter, and end-consumer—and is structured to function as a smart contract, whereby each party can assume responsibility for maintaining optimal supply chain conditions. This practical implementation demonstrates the feasibility of low-cost, scalable IoT architectures that bridge the gap between conceptual cyber-physical models and real-world operational deployment in pharmaceutical cold chains.

3-6. Cybersecurity, Protocol Design, and Technology Governance

Cybersecurity and governance issues are increasingly recognized as major adoption barriers, particularly due to the sensitive nature of pharmaceutical data and regulatory requirements. Safkhani et al. (2020) developed lightweight RFID security protocols to preserve data integrity and protect tracking systems against attacks. Coustasse et al. (2016) analyzed regulatory barriers limiting RFID adoption at scale. In blockchain governance research, Tseng et al. (2018) examined governance mechanisms based on blockchain frameworks, while Lingayat et al. (2021) discussed the role of blockchain in ensuring authenticity and data integrity in pharmaceutical supply chains; however, the paper was later retracted and should therefore be interpreted cautiously. Additionally, Gruchmann et al. (2023) conducted a cost–benefit analysis of blockchain deployment from a transaction-cost perspective. The reviewed evidence suggests that governance frameworks, secure authentication protocols, and privacy-preserving mechanisms are essential for large-scale adoption, particularly when IoT systems are deployed across multiple organizations and jurisdictions.

3-7. Systematic Reviews and Integrative Frameworks

Several review studies have summarized existing evidence and provided conceptual roadmaps for future research. Fernando et al. (2019) identified critical success factors for blockchain adoption in the pharmaceutical sector, while Surjandy et al. (2019) reviewed benefits and challenges of blockchain-based systems. Ghadge et al. (2023) proposed a comprehensive conceptual implementation framework. Taj et al. (2023)

presented a systematic review of IoT implementation in supply chain management, and Scaccia (2020) provided an overview of IoT-driven transparency and efficiency improvements. Complementing earlier review studies, Habazin et al. (2025) conducted a systematic review of artificial intelligence applications specifically in cold chain and reverse logistics. Their analysis examined the technological foundations and baseline capabilities of AI in logistics, explored how AI supports sustainability-driven reverse logistics, and assessed the potential of AI to enable integrated management of cold and general supply chains. The review identified that AI advancements are progressively improving the resilience and efficiency of cold-chain systems while enabling integration across previously fragmented logistics domains. This recent synthesis reinforces the growing consensus that AI is not merely an auxiliary tool but a foundational enabler for sustainable, integrated cold-chain management.

3-8. Synthesis and Research Gaps

The reviewed literature confirms that pharmaceutical supply chains require high levels of visibility, traceability, and responsiveness due to strict regulatory requirements, multi-stakeholder coordination challenges, and the sensitivity of temperature-controlled products. In recent years, the relevance of this issue has been further emphasized by global crises such as the COVID-19 pandemic, where disruptions in vaccine and medicine distribution highlighted the importance of resilient and digitally enabled supply chain systems. Overall, four technological pillars have emerged as key enablers of pharmaceutical supply chain digitalization: (*i*) sensors and identification technologies (RFID), (*ii*) real-time monitoring systems, (*iii*) blockchain-based distributed ledgers, and (*iv*) AI-driven analytics and machine learning models. These technologies collectively enable end-to-end traceability, authenticity verification, predictive decision-making, and operational optimization. However, despite significant progress, major challenges remain. From a technical perspective, data security vulnerabilities, lack of standardized communication protocols, and device interoperability issues limit scalability. From an economic and organizational perspective, high initial investment costs, integration complexity, and workforce training requirements hinder adoption. From a governance and regulatory standpoint, unresolved issues related to data ownership, liability, and compliance with international regulations remain critical barriers. Moreover, the literature reveals important research gaps: limited long-term field studies evaluating operational and economic effectiveness at full scale, insufficient systematic comparisons between competing architectures (e.g., permissioned vs. public blockchain implementations, alternative RFID protocols, and edge vs. cloud computing paradigms), and a lack of comprehensive risk–benefit analyses simultaneously incorporating technical, economic, legal, and sustainability dimensions.

Given the energy-intensive nature of cold-chain logistics, future studies should increasingly focus on quantifying energy efficiency gains, evaluating carbon footprint reduction, and developing energy-aware AI optimization frameworks for refrigerated transportation and warehousing. As discussed in Section 3.3, recent integrative frameworks such as Sheng et al. (2026) have demonstrated that the synergistic deployment of AI, big data, and energy-aware IoT can reduce energy consumption by up to 35% and lower emissions by 25%, offering a compelling evidence base for the sustainability benefits of digital transformation in pharmaceutical cold chains. Pilot implementations, interdisciplinary evaluations, and standardized governance models are necessary to facilitate sustainable and scalable adoption of IoT-enabled pharmaceutical supply chain solutions. In summary, the literature demonstrates that IoT, blockchain, RFID, and AI technologies can significantly enhance transparency, safety, efficiency, and sustainability in pharmaceutical supply chains. However, achieving large-scale implementation requires addressing technical interoperability challenges, cybersecurity risks, and the economic feasibility of deployment through robust cost–benefit and sustainability-oriented assessments.

4. Results Analysis

This study is based on data extracted from 76 papers focused on the application of the IoT in pharmaceutical supply chains. Information on pharmaceutical supply chains was collected through systematic review and analysis of published research and prepared for structural and thematic analysis. In this section, we first examine the distribution of research by annual publication counts and quantitative indicators. Then, qualitative aspects such as multi-objective focus, utilization of metaheuristic methods, and foresight-oriented approaches are analyzed. Detailed analyses for each indicator are provided to clearly reveal research trends, strengths, and gaps in the literature.

4-1. Distribution by Year

The temporal distribution of papers highlights how the research community's attention to the IoT in pharmaceutical supply chains has evolved over time.

The temporal distribution of the 76 reviewed studies reveals how research attention to IoT, blockchain, and AI technologies in pharmaceutical supply chains has evolved. As shown in Fig. 1, publications before 2016 were sparse, with only 9 papers appearing between 2009 and 2015, reflecting the early conceptual phase of IoT adoption and limited awareness of its pharmaceutical applications. A gradual increase began in 2016–2018 (11 papers), coinciding with infrastructure maturation and growing recognition of digital traceability benefits. A significant surge occurred in 2019–2021 (26 papers), driven in large part by the COVID-19 pandemic, which highlighted the urgent need for resilient, transparent, and digitally enabled supply chains for vaccines and essential medicines. Research output peaked in 2023 (12 papers) and remained substantial through 2024–2025 (12 papers combined), with a further contribution in early 2026 (1 paper). This sustained activity suggests that the field has entered a consolidation phase, characterized by an increasing emphasis on field validation, cost–benefit analysis, and real-world deployment of integrated IoT–blockchain–AI systems. Key insights from this temporal analysis include:

- Research attention has grown steadily, with a clear inflection point during the pandemic.
- The post-2021 period reflects a shift from conceptual proposals toward implementation-oriented studies.
- The continued publication rate in 2023–2025 indicates that IoT-, blockchain-, and AI-enabled pharmaceutical supply chains remain a high-potential research domain.
- Future studies are expected to focus on pilot implementations, energy-aware optimization, and standardized evaluation frameworks.

4-2. Distribution by Technology

This section reviews papers based on the technologies employed in pharmaceutical supply chains, highlighting adoption trends, technology evolution, and research focus areas such as RFID, IoT, blockchain, AI, and machine learning.

As shown in Fig. 2, the most frequently studied technologies are IoT and blockchain, each appearing in 20 papers, reflecting their central role in real-time monitoring, data integrity, and secure transaction logging. AI and machine learning (11 papers) represent a rapidly growing focus, particularly for predictive analytics and energy-aware optimization. The strong presence of hybrid categories, especially IoT–blockchain (10 papers), confirms the trend toward integrated architectures that combine sensing, secure data sharing, and automated decision-making. IoT–AI (3 papers) and blockchain–AI (2 papers) are still emerging but indicate increasing interest in embedding intelligence directly into supply chain operations.

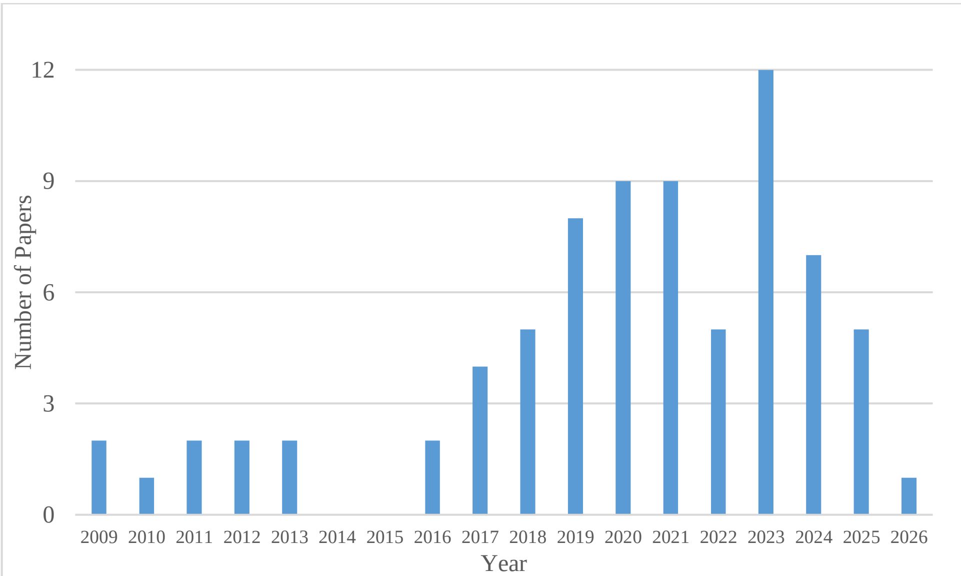

Fig. 1. Number of papers per year

RFID (9 papers) continues to receive attention for item-level tracking, and the IoT–RFID combination (1 paper) remains a niche area. Overall, the distribution underscores that research is shifting from isolated technology applications toward synergistic, multi-technology frameworks that simultaneously enhance traceability, efficiency, and sustainability.

Blockchain provides a distributed, immutable ledger, ensuring secure and transparent recording of transactions and events, supporting drug authenticity verification and reducing human errors. Research suggests that developing blockchain infrastructure and establishing common standards can enhance adoption, particularly in developing countries where counterfeit drugs are prevalent. RFID tags enable rapid identification and tracking of pharmaceutical units, providing accurate inventory and location data, though fewer studies focus exclusively on RFID. Optimizing tag design, reducing costs, and improving reliability could enhance adoption, especially when combined with complementary technologies for quality assurance. AI and machine learning facilitate analysis of historical data, prediction of trends and anomalies, and improved supply chain decision-making. These systems can automatically detect issues and suggest optimization strategies, reducing costs and increasing efficiency. However, lack of integrated data platforms and skilled personnel limits their full potential.

To address the limitations of individual technologies, researchers have explored combinations for synergistic benefits. IoT–blockchain integration enables real-time sensor data recording in secure, immutable ledgers. IoT–RFID integration improves data capture and centralized processing, enhancing inventory management. Blockchain–AI integration facilitates secure data analysis and anomaly detection, while IoT–AI enables actionable insights from real-time data. Prioritization of technologies was based on publication count and technological maturity. IoT and blockchain ranked highest in research attention and problem-solving capacity due to real-time monitoring and security capabilities. RFID and IoT–blockchain integration were medium priority, while AI and emerging hybrid solutions were lower priority, reflecting ongoing development and integration challenges. Overall, combined technologies improve product traceability, transparency, and supply chain responsiveness, but successful implementation requires multidisciplinary expertise, coordination, investment, and mitigation of security risks.

4-3. Distribution by Research Method

Research on IoT applications in pharmaceutical supply chains employs qualitative, quantitative, and mixed-method approaches. Of the 76 reviewed studies, 37 adopted a clearly identifiable empirical research method; the remaining 39 are systematic reviews, conceptual frameworks, or architecture proposals without primary empirical data. As shown in Fig. 3, quantitative methods dominate among empirical studies (27 papers), reflecting the strong emphasis on simulation, performance evaluation, and optimization modeling, particularly in energy-aware and predictive analytics research. Qualitative approaches are used in 9 studies, primarily for case studies, governance analysis, and organizational adoption inquiries.

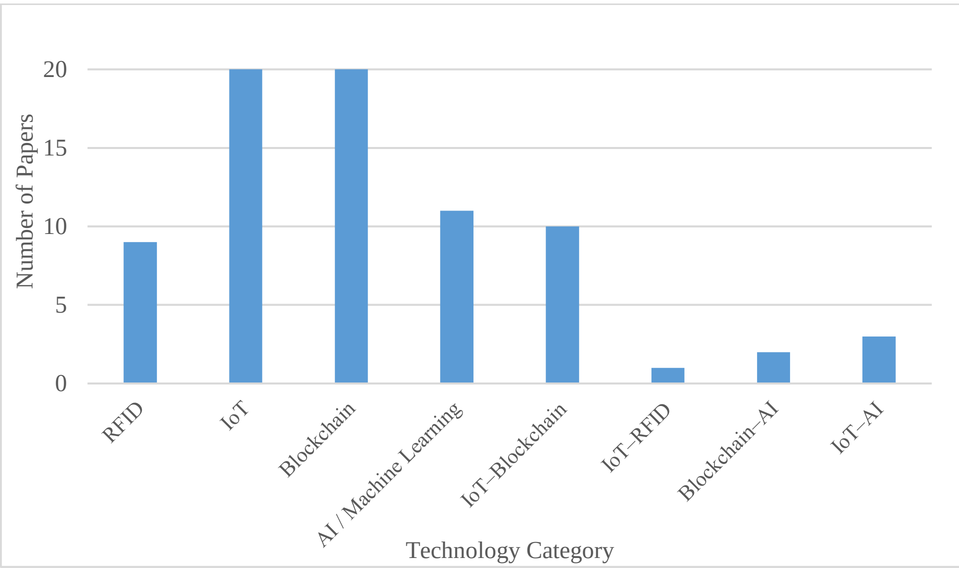

Fig. 2. Number of papers by technology.

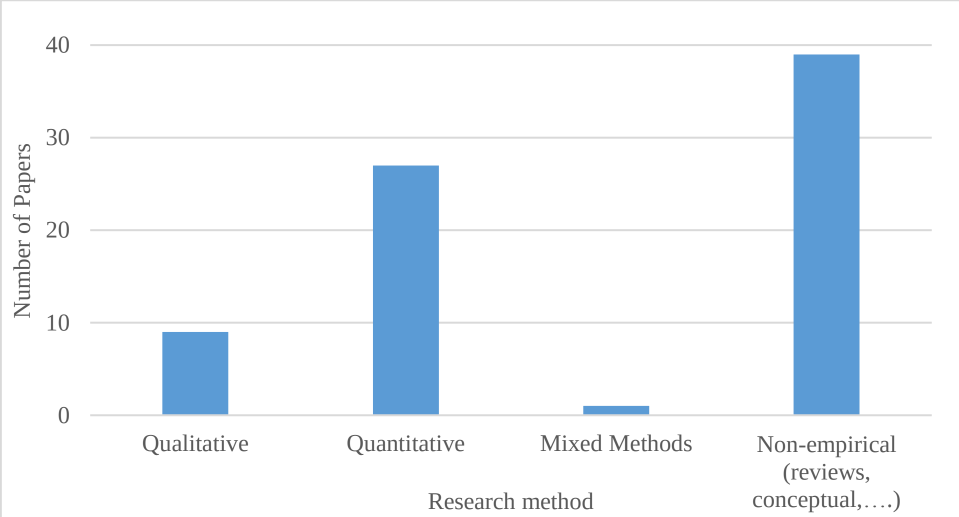

Fig. 3. Number of papers by research method.

Only 1 study employed a mixed-methods design, combining qualitative insights with quantitative validation. This distribution indicates that while quantitative rigor is well-established, the field would benefit from a greater integration of qualitative and mixed-methods approaches to capture both operational performance and the contextual, organizational factors that influence technology adoption in pharmaceutical supply chains.

4-4. Distribution by Technology–Method Combination

Fig. 4 illustrates the distribution of research methods across technology categories. Quantitative methods are dominant in IoT (10 studies), blockchain (8 studies), and RFID (4 studies), reflecting the emphasis on performance evaluation, simulation, and optimization in these domains. AI/ML and emerging hybrid technologies (blockchain–AI, IoT–RFID) rely exclusively on quantitative approaches, consistent with their focus on algorithmic development and simulation-based validation. Qualitative methods are concentrated in IoT (4 studies) and RFID (3 studies), where case studies and organizational analyses are common. Notably, mixed-methods designs remain rare (1 study, in RFID), and IoT–AI currently lacks empirical studies altogether. This distribution suggests that while quantitative rigor is well-established, the field would benefit from qualitative and mixed-methods research in emerging technology combinations to capture both technical performance and contextual implementation factors.

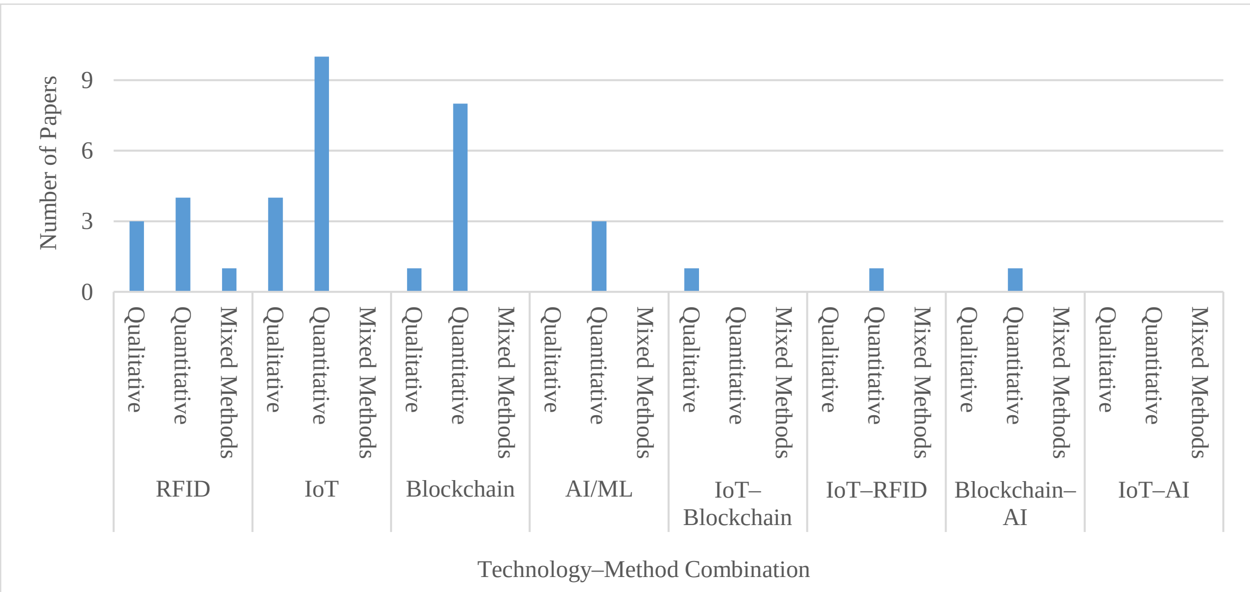

Fig. 4. Number of papers by combination of research method and technology.

4-5. Single-Objective vs. Multi-Objective Models

Among the 20 modeling studies identified in the review, 15 (75%) adopt a single-objective formulation, typically minimizing prediction error, energy consumption, or spoilage rate, while 5 (25%) employ multi-objective models that simultaneously balance cost, quality, environmental impact, and service levels (see Fig. 5). Multi-objective models are primarily used in strategic supply chain network design and integrated logistics optimization, whereas single-objective models dominate forecasting, anomaly detection, and real-time control tasks.

4-6. Metaheuristic Applications

Metaheuristic algorithms were employed in only 2 of the 20 modeling studies (10%), as illustrated in Fig. 6. These methods were applied to solve complex multi-objective network design problems where exact solvers are impractical. The remaining studies relied on classical machine learning, reinforcement learning (e.g., Q-learning), or exact optimization techniques. This indicates a nascent but growing adoption of metaheuristics, constrained by the need for advanced expertise and longer development cycles.

4-7. Uncertainty Considerations

Uncertainty is explicitly accounted for in 17 of the 20 modeling papers (85%) (see Fig. 7).

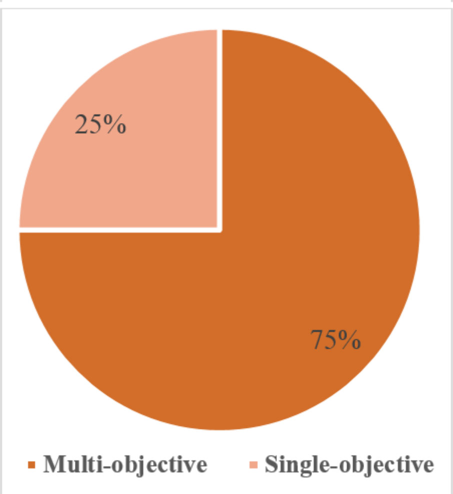

Fig. 5. Percentage of single-objective and multi-objective functions in modeling papers.

Common sources include ambient temperature variability, demand fluctuations, and sensor noise. Strategies to handle uncertainty include stochastic programming, robust optimization, and reinforcement learning in inherently stochastic environments. The high prevalence confirms that model realism is a priority in pharmaceutical cold-chain research.

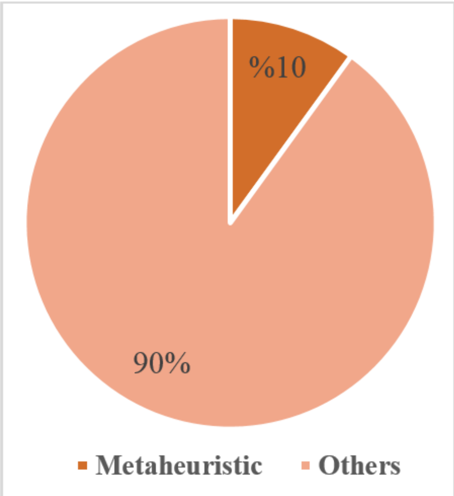

Fig. 6. Percentage of metaheuristic papers.

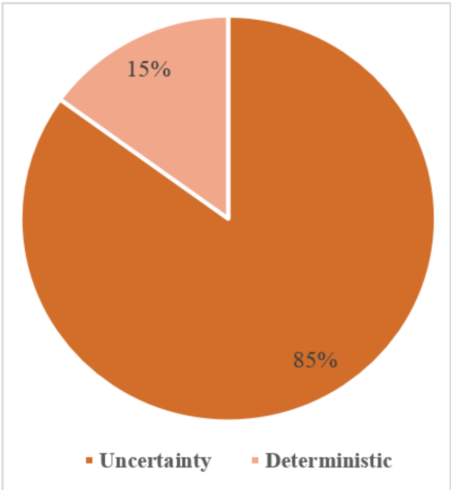

Fig. 7. Percentage of addressing uncertainty.

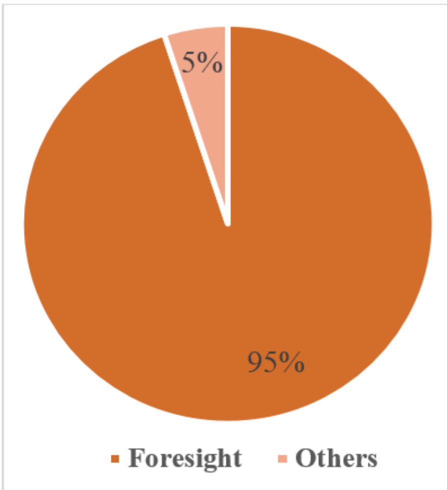

Fig. 8. Percentage of foresight studies.

Foresight is addressed in 19 studies (95%) (see Fig. 8), as nearly all modeling papers discuss future research directions, scalability, or field validation. Together, these figures show that while the modeling literature is increasingly robust in handling uncertainty and planning for future work, there is room for greater methodological diversity through multi-objective and metaheuristic approaches.

5. Future Research and Practical Recommendations

The reviewed literature demonstrates that IoT, blockchain, RFID, and AI technologies have substantial potential to improve transparency, traceability, energy efficiency, and operational resilience in pharmaceutical supply chains. However, most existing studies remain limited to conceptual frameworks, simulation-based analyses, or small-scale implementations. Consequently, future research should increasingly emphasize scalable architectures, real-world validation, interoperability, and quantitative evaluation of operational and sustainability impacts.

From a technical perspective, future studies should focus on the development of integrated edge–cloud–blockchain architectures capable of supporting real-time monitoring while minimizing latency, communication overhead, and energy consumption. In parallel, lightweight and explainable AI models are needed to enable reliable deployment in resource-constrained cold-chain environments where computational capacity, connectivity, and data quality may vary significantly. Existing reinforcement learning and machine learning approaches have demonstrated promising results in temperature control, anomaly detection, and routing optimization; however, their practical applicability under dynamic operational conditions remains insufficiently validated.

Another important research direction concerns the development of multi-objective and uncertainty-aware optimization models. Most current studies focus on a single operational objective, whereas real pharmaceutical supply chains require simultaneous consideration of cost, service level, energy consumption, environmental impact, and product quality. Future modeling efforts should therefore incorporate stochastic demand, ambient temperature variability, transportation disruptions, and sensor uncertainty within integrated optimization frameworks. Comparative analyses between exact methods, reinforcement learning approaches, and metaheuristic algorithms would also provide valuable insights regarding scalability and computational efficiency in large-scale cold-chain applications.

Despite the increasing number of conceptual and simulation-based studies, empirical validation remains limited. Additional pilot implementations and longitudinal case studies are necessary to evaluate the operational feasibility, economic viability, and scalability of IoT-enabled pharmaceutical supply chain systems under real-world conditions. In particular, future research should investigate measurable performance indicators such as spoilage reduction, energy savings, traceability accuracy, response time, and total implementation cost. Comparative field studies across different pharmaceutical contexts—including vaccines, biologics, and high-value temperature-sensitive medicines—would further improve the generalizability of existing findings.

Cybersecurity, privacy, and interoperability also remain critical barriers to large-scale adoption. Future work should prioritize the design of secure and standardized communication frameworks capable of supporting multi-organizational data exchange while preserving confidentiality and regulatory compliance. In particular, blockchain governance mechanisms, lightweight authentication protocols, and privacy-preserving analytics require further investigation to balance transparency with data protection requirements. Moreover, the lack of unified interoperability standards continues to complicate integration among manufacturers, logistics providers, healthcare institutions, and regulatory agencies.

From an economic and managerial perspective, the literature indicates a need for more rigorous cost–benefit and sustainability assessments. Although many studies highlight the potential advantages of digital transformation, relatively few provide quantitative evidence regarding return on investment, long-term maintenance costs, or organizational implementation challenges. Future studies should therefore integrate operational, environmental, and economic evaluation criteria to support evidence-based managerial and policy decisions regarding technology adoption.

Finally, successful digital transformation in pharmaceutical supply chains will require stronger interdisciplinary collaboration among researchers, technology providers, healthcare organizations, logistics operators, and policymakers. Beyond technological innovation alone, sustainable implementation depends on workforce readiness, organizational adaptation, regulatory alignment, and the establishment of reliable governance structures. Consequently, future research should adopt a more holistic perspective that simultaneously addresses technical performance, operational feasibility, cybersecurity, sustainability, and human factors in order to support scalable and resilient pharmaceutical supply chain ecosystems.

6. Conclusion

This systematic review synthesized findings from 76 studies to examine the role and impact of Internet of Things (IoT), blockchain, Radio Frequency Identification (RFID), Artificial Intelligence (AI), and machine learning in pharmaceutical supply chains. The review consolidates empirical and theoretical evidence on how these technologies can improve transparency, safety, and operational efficiency, while identifying the technical, organizational, and regulatory barriers that remain. Key insights from the analysis include:

- *Technology focus:* IoT and blockchain have received the most research attention, both independently and in combination, showing high potential for enhancing traceability, immutable event recording, and fraud reduction. AI and machine learning are increasingly integrated for predictive analytics and energy-aware optimization.
- *Modeling trends:* Multi-objective models account for 25% of quantitative studies, and metaheuristic methods are used in 10%, indicating room for methodological expansion. Uncertainty is explicitly considered in 85% of models, and foresight is present in 95%.
- *Practical applications:* IoT integrated with AI improves demand forecasting, anomaly detection, and route optimization; IoT combined with blockchain ensures secure and transparent event recording; RFID plays a practical role in unit-level tracking and inventory management.
- *Challenges:* Security and privacy concerns, lack of unified standards, high implementation costs, data quality issues, and organizational and regulatory barriers remain significant limiting factors.

From an industrial perspective, the review offers a framework for piloting stage-wise deployments with defined KPIs, selecting appropriate edge–cloud–blockchain architectures, and establishing security and data standards. Economic analyses and proposed business models can reduce investment risk and enhance project financial justification. Service-level benefits include reduced waste, improved distribution accuracy, and faster patient access to essential drugs, thereby increasing consumer trust. Environmental and social benefits include optimized energy consumption and reduced greenhouse gas emissions through AI-driven, intelligent resource management.

6-1. Limitations of this Review

This review has several limitations that should be acknowledged. First, the systematic search was limited to three major interdisciplinary databases—Scopus, Web of Science, and PubMed. Consequently, relevant studies published in smaller, specialized, or regional outlets not indexed in these databases may have been inadvertently omitted. Second, despite a systematic search strategy, the possibility of publication bias cannot be ruled out, as studies reporting successful implementations or positive results are more likely to be published than those with negative or inconclusive findings. Third, no formal quality appraisal tool was applied to assess the methodological rigor of the included primary studies; consequently, findings should be interpreted with an awareness of varying evidence strength across the reviewed literature. Fourth, while the thematic synthesis captured the breadth of the field, the classification of studies into a single primary domain may have oversimplified the contributions of inherently multidisciplinary works. Finally, the rapid pace of technological development in IoT, AI, and blockchain means that very recent innovations may not be fully represented, particularly those emerging in 2026.

Ultimately, realizing the full benefits of digital technologies in pharmaceutical supply chains requires an integrated approach: simultaneous technological development, standardization, field validation, supportive policies, and capacity-building. Only through such a holistic strategy can these innovations be transformed into scalable, sustainable, and reliable solutions for the pharmaceutical industry.

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