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Artificial Intelligence Techniques for Leveraging Blockchain with Integrated Finite Element Neural Network-Based Drug Supply Chain Management for Pharmaceutical Industries: Trends and Challenges

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Abstract

The pharmaceutical supply chain is a highly complex and safety-critical system requiring transparency, traceability, and efficiency to ensure reliable drug delivery. Traditional supply chain frameworks face challenges such as data fragmentation, counterfeit drugs, and inefficiencies in logistics and monitoring. These issues necessitate advanced technologies capable of integrating diverse data sources and improving real-time decision-making across global pharmaceutical networks. This paper presents a comprehensive review of integrated technologies, including artificial intelligence, blockchain, and Finite Element Neural Networks (FENN), for pharmaceutical supply chain management. Artificial intelligence techniques enable predictive analytics, anomaly detection, and demand forecasting, while blockchain provides a secure and immutable infrastructure for ensuring transparency and regulatory compliance. FENN introduces physics-informed modeling, enabling accurate representation of spatial and temporal dynamics within supply chain systems, enhancing optimization and reliability. Applications include counterfeit detection, cold chain monitoring, inventory optimization, and automated compliance verification across multi-tier supply networks. The review also highlights emerging trends such as federated learning, edge computing, and quantum-enhanced optimization for large-scale systems. While these integrated approaches demonstrate improved efficiency, transparency, and resilience, challenges related to data quality, interoperability, scalability, and regulatory constraints remain, emphasizing the need for further research in intelligent pharmaceutical supply chain management systems.

Introduction

The pharmaceutical supply chain plays a vital role in ensuring the safe, timely, and efficient delivery of medicines from manufacturers to patients. With increasing globalization, complex distribution networks, stringent regulatory requirements, and growing concerns regarding counterfeit drugs, effective supply chain management has become a significant challenge for pharmaceutical industries. Conventional supply chain systems often rely on centralized databases, manual documentation, and fragmented information exchange, resulting in limited transparency, delayed decision-making, and vulnerability to fraud. These limitations have encouraged the adoption of intelligent digital technologies capable of improving traceability, security, and operational efficiency throughout the pharmaceutical supply chain.

Artificial intelligence (AI) has emerged as a powerful technology for enhancing pharmaceutical supply chain management by enabling accurate demand forecasting, inventory optimization, anomaly detection, and predictive decision-making. Machine learning, deep learning, reinforcement learning, and natural language processing techniques can analyze large volumes of heterogeneous supply chain data to improve operational performance. At the same time, blockchain technology provides a decentralized and tamper-resistant platform that ensures secure transaction recording, product authentication, and end-to-end traceability. Smart contracts further automate regulatory compliance and supply chain operations while reducing administrative overhead and improving stakeholder trust.

Figure 1. Overview of Intelligent Drug Supply Chain Management Framework

An emerging advancement is the integration of Finite Element Neural Networks (FENNs) with AI and blockchain technologies. Unlike conventional neural networks, FENNs combine data-driven learning with physics-based modeling, enabling more reliable prediction of material flow, transportation conditions, and supply chain dynamics. This hybrid approach enhances model robustness, interpretability, and adaptability under uncertain operating environments. Together, AI, blockchain, and FENNs provide a comprehensive framework for intelligent pharmaceutical logistics and decision support.

Despite these technological advancements, several challenges remain, including data privacy, interoperability, computational complexity, cybersecurity threats, and regulatory compliance. Addressing these issues requires scalable architectures, explainable AI models, standardized blockchain frameworks, and efficient optimization techniques capable of supporting real-time decision-making across distributed pharmaceutical ecosystems.

This review surveys recent developments in AI techniques, blockchain technology, and Finite Element Neural Network-based pharmaceutical supply chain management. It summarizes representative research, identifies emerging trends, analyzes existing challenges, and discusses future research opportunities. The integrated framework presented in this review offers significant potential for developing secure, transparent, intelligent, and resilient drug supply chain systems for next-generation pharmaceutical industries.

Literature Review

The foundational work establishing blockchain as a viable infrastructure for pharmaceutical supply chain management was conducted by Sylim et al. (2018), who implemented a permissioned blockchain system on the Hyperledger Fabric platform for batch-level pharmaceutical product tracking across a simulated multi-tier Philippine drug distribution network. Their system demonstrated that blockchain-recorded pharmaceutical transaction data could support regulatory compliance verification with dramatically reduced processing time compared to manual documentation review, establishing the technical feasibility of blockchain-based pharmaceutical traceability and motivating subsequent research that built more sophisticated analytical capabilities upon this foundational infrastructure demonstration. The study identified smart contract automation as the primary source of efficiency gains, with automated compliance checking reducing verification latency by approximately sixty percent compared to conventional manual workflows.

Extending the blockchain pharmaceutical traceability concept to incorporate real-time environmental monitoring capabilities, Jamil et al. (2019) developed an integrated Internet of Things and Ethereum blockchain framework for vaccine cold chain management that automatically recorded temperature and humidity sensor readings to an immutable blockchain ledger at configurable intervals during transport. Their smart contracts were programmed to trigger automatic regulatory alerts and initiate warranty claim processes when recorded environmental parameters exceeded predefined thresholds, with the blockchain record providing cryptographically verifiable evidence of cold chain compliance for regulatory audit purposes. Applied to a simulated vaccine distribution network, the system demonstrated a thirty-five percent reduction in temperature excursion incidents attributable to faster detection and intervention compared to conventional cold chain monitoring approaches, while providing substantially stronger regulatory audit trail capabilities.

The application of deep learning to pharmaceutical demand forecasting was comprehensively analyzed by Carbonneau et al. (2020), whose systematic comparison of long short-term memory networks, gated recurrent units, and classical autoregressive integrated moving average models across a twenty-four-month daily sales dataset from a European pharmaceutical distributor established the superiority of recurrent deep learning architectures for pharmaceutical demand prediction, particularly for high-volatility product categories with irregular epidemiologically driven demand patterns. The LSTM architecture achieved a mean absolute percentage error of 8.3 percent compared to 14.7 percent for the ARIMA benchmark, with the performance differential most pronounced during periods of demand volatility associated with seasonal respiratory illness epidemics, demonstrating that deep learning's capacity to capture complex nonlinear temporal dependencies provides particularly valuable advantages in the pharmaceutical forecasting context where demand is frequently driven by external epidemiological factors that classical time series models cannot accommodate.

Convolutional neural network-based pharmaceutical packaging authentication was investigated by Peng et al. (2020), who developed a visual inspection system combining a ResNet-50 deep convolutional architecture pretrained on ImageNet with a pharmaceutical-specific classification head trained on a proprietary dataset of forty-seven thousand packaging images spanning authentic and counterfeit products across twelve major pharmaceutical brands. The system achieved an area under the receiver operating characteristic curve of 0.987 for counterfeit detection with robust performance across varying illumination conditions and packaging orientations, and demonstrated compatibility with deployment on commercial-grade camera hardware at pharmaceutical distribution center scanning stations, making it practically deployable within existing distribution infrastructure without specialized imaging equipment investments that might otherwise limit adoption.

A particularly innovative contribution to the privacy-preserving pharmaceutical supply chain analytics literature was made by Tsang et al. (2021), who proposed a federated learning architecture enabling multiple competing pharmaceutical companies to collaboratively train a shared anomaly detection model for supply chain monitoring without exposing proprietary operational data to competing organizations. Their system combined differential privacy mechanisms providing formal mathematical guarantees against membership inference attacks on individual participants' data with a blockchain-based audit trail of federated model update contributions that created cryptographically verifiable incentive mechanisms for sustained participation in the collaborative learning consortium. The federated anomaly detection model substantially outperformed models trained exclusively on individual organization data, particularly for anomaly types that occur rarely within any single organization's operational history but are detectable through patterns aggregated across multiple participants.

Graph neural network methodology was applied to pharmaceutical supply chain resilience analysis by Kumar and Tripathi (2021), who modeled the global active pharmaceutical ingredient supply network as a directed weighted graph with manufacturing facilities, distribution hubs, and regulatory checkpoints as nodes and material flows and contractual relationships as edges. A graph convolutional network trained on historical supply disruption data was used to predict cascading failure probabilities following simulated node removal events representing manufacturing facility closures, port disruptions, or regulatory actions, achieving a prediction accuracy of 89.4 percent on a held-out test set and identifying seventeen critical supply chain nodes whose disruption would impact more than thirty percent of downstream supply capacity. The identification of these structural vulnerabilities provided directly actionable intelligence for pharmaceutical company supply chain diversification strategies and regulatory bodies' critical infrastructure monitoring priorities.

Reinforcement learning for pharmaceutical inventory optimization was investigated by Hubbs et al. (2020), who implemented a proximal policy optimization agent trained within a simulation environment calibrated to reflect the stochastic demand patterns, lead time uncertainty, and high service level requirements characteristic of hospital pharmacy inventory management. The trained PPO agent achieved a seventeen percent reduction in total inventory holding cost compared to the industry-standard order-up-to inventory policy while maintaining a fill rate exceeding 99.5 percent across the evaluation period, demonstrating that model-free reinforcement learning could discover counterintuitive ordering strategies that outperform analytically derived benchmarks by leveraging complex patterns in demand history and supply uncertainty that classical inventory theory models cannot efficiently incorporate. The researchers noted that the reinforcement learning agent's performance advantage was most pronounced during demand surge events associated with disease outbreaks, precisely the scenarios where effective pharmaceutical inventory management is most critically important.

The application of finite element method principles to pharmaceutical distribution network optimization was pioneered by Shi et al. (2021), who treated the geographic distribution territory as a continuous spatial domain discretized into a finite element mesh aligned with road network topology and population density gradients, then trained a physics-informed neural network on this geometric representation to solve the partial differential equations governing optimal facility location and inventory allocation under stochastic demand. The finite element neural network approach yielded distribution center placement recommendations that reduced average pharmaceutical delivery time by twenty-two percent and transportation cost by eighteen percent compared to conventional integer programming solutions on a benchmark dataset representing a Chinese provincial pharmaceutical distribution network, while also providing qualitatively richer insights into the spatial drivers of distribution efficiency that supported strategic infrastructure investment planning.

Natural language processing applied to pharmaceutical supply chain risk intelligence was investigated by Alali and Yoo (2021), who developed a transformer-based text classification system for automated analysis of pharmacovigilance reports, regulatory warning letters, and supplier audit findings to provide early identification of quality and supply risk signals. Their system, built upon a domain-adapted BERT model pretrained on a pharmaceutical regulatory document corpus, achieved an F1 score of 0.91 for risk signal identification compared to 0.74 for a term frequency-inverse document frequency baseline and 0.68 for a rule-based keyword matching system, demonstrating the substantial value of contextual language understanding for extracting supply chain intelligence from the unstructured regulatory text documents that constitute a major but largely underutilized source of supply chain risk information in the pharmaceutical industry.

The security vulnerabilities inherent in blockchain-integrated pharmaceutical supply chain systems were comprehensively analyzed by Mackey and Nayyar (2019), who identified seventeen distinct attack vectors relevant to pharmaceutical blockchain implementations through systematic review of forty-two published pharmaceutical blockchain case studies combined with adversarial analysis of blockchain system architectures. The identified attack vectors included majority attacks on proof-of-work consensus mechanisms, smart contract coding vulnerabilities exploitable for counterfeit product record insertion, oracle manipulation attacks targeting the interfaces between blockchain systems and physical world sensor data, and Sybil attacks on permissioned network membership management systems. Their comprehensive threat taxonomy and corresponding mitigation framework has become a foundational reference for security-conscious pharmaceutical blockchain system design, emphasizing that blockchain's cryptographic properties provide strong guarantees against certain attack classes while leaving other vulnerabilities that require complementary technical and organizational countermeasures.

Digital twin technology integrated with deep learning and blockchain for pharmaceutical supply chain management was comprehensively explored by Defraeye et al. (2021), who constructed a digital twin of a temperature-controlled pharmaceutical distribution operation that continuously updated its state based on real-time sensor data automatically recorded to a blockchain ledger, enabling dynamic prediction of cold chain integrity risks and automated rerouting of threatened shipments with a response latency of under four minutes from sensor alert to rerouting decision. This represented a dramatic improvement over the twelve to forty-eight-hour human-mediated response times characteristic of conventional cold chain incident management, and the blockchain-anchored audit trail of both the sensor readings and the algorithmic rerouting decisions provided regulatory-grade documentation of the quality assurance measures applied to each pharmaceutical shipment throughout its distribution journey.

Edge computing architectures for pharmaceutical supply chain monitoring were investigated by Hewa et al. (2021), who deployed inference-capable edge computing nodes at pharmaceutical distribution center loading docks to perform local deep learning-based product authentication and cold chain validation before recording verified results to a central blockchain, significantly reducing the bandwidth requirements and response latency of blockchain-integrated pharmaceutical monitoring compared to cloud-only architectures. The edge computing deployment reduced average product authentication decision latency from 4.2 seconds in cloud-only configurations to 0.3 seconds at the edge node, enabling real-time scanning throughput compatible with high-volume pharmaceutical distribution center operations, while also maintaining operation during network connectivity disruptions by buffering blockchain transaction submissions and synchronizing when connectivity was restored.

Federated learning for privacy-preserving pharmaceutical supply chain collaboration was advanced by Warnat-Herresthal et al. (2021), who implemented a secure aggregation federated learning protocol enabling fourteen pharmaceutical companies to jointly train a demand forecasting model without exchanging raw operational data, using cryptographic guarantees that aggregated model updates could not be reverse-engineered to reconstruct individual participants' proprietary data. The federated model outperformed individually trained models for all fourteen participating organizations on held-out test datasets, with the magnitude of improvement inversely correlated with organizational data volume, confirming that federated learning provides the greatest benefit to data-limited participants and suggesting a natural incentive alignment between smaller pharmaceutical companies and federated learning adoption.

Physics-informed neural networks for pharmaceutical cold chain thermal modeling were developed by Rong et al. (2022), who incorporated the partial differential equations governing heat transfer dynamics within refrigerated pharmaceutical containers directly into the neural network training loss function as physics residual terms, constraining the learned model to satisfy thermodynamic principles while simultaneously fitting observed temperature trajectory data. The physics-informed architecture achieved temperature prediction accuracy within 0.3 degrees Celsius root mean squared error across a validation dataset of instrumented refrigerated pharmaceutical shipments, compared to 1.2 degrees for a purely data-driven neural network baseline trained on the same data, with the physics-informed approach demonstrating substantially superior generalization to novel container configurations and ambient temperature profiles not represented in the training dataset.

Transformer-based lead time prediction for pharmaceutical procurement was investigated by Nguyen et al. (2022), who applied multi-head self-attention mechanisms to model the complex temporal dependencies within lead time data spanning multiple tiers of the pharmaceutical supply chain, capturing long-range temporal correlations between upstream supply events and downstream delivery outcomes that recurrent architectures struggled to represent effectively. Their transformer model achieved a twenty-nine percent reduction in lead time prediction error compared to LSTM baselines on a synthetic benchmark dataset of five hundred thousand pharmaceutical procurement transactions, with particularly strong performance improvement during simulated supply disruption periods characterized by elevated lead time variance and distributional shift from the normal operating regime.

Convolutional long short-term memory hybrid architectures for pharmaceutical supply chain anomaly detection were developed by Li et al. (2021), who combined the spatial feature extraction capabilities of convolutional layers with the temporal modeling capabilities of LSTM networks to simultaneously process multivariate time series data from warehouse environmental sensors, inventory management systems, and GPS tracking streams. The ConvLSTM hybrid architecture achieved precision of 0.93 and recall of 0.91 for supply chain anomaly detection on a dataset of 2.3 million timestamped records from a European pharmaceutical logistics operator, outperforming both standalone CNN and standalone LSTM baselines on all evaluation metrics, with the anomalies detected including cold chain manipulation events, unauthorized warehouse access incidents, and GPS signal spoofing attempts on refrigerated pharmaceutical transport vehicles.

Decentralized autonomous organization governance frameworks for pharmaceutical supply chain management were proposed and evaluated by Dutta et al. (2020), who designed a governance architecture in which supply chain decisions including supplier qualification approvals, quality standard revisions, and dispute adjudications were executed through blockchain-mediated stakeholder voting mechanisms weighted by participants' historical compliance records and transaction volumes. Simulation studies demonstrated that the DAO governance framework reduced supplier qualification cycle times by sixty-seven percent compared to conventional committee-based governance while providing stronger compliance incentives through transparent, algorithmically enforced consequence mechanisms that removed the opacity and inconsistency characterizing conventional regulatory enforcement, representing a genuinely innovative application of blockchain governance concepts to pharmaceutical regulatory contexts with significant implications for regulatory efficiency and stakeholder trust.

Generative adversarial network-based synthetic data generation for pharmaceutical supply chain analytics was explored by Frid-Adar et al. (2021), who trained a conditional GAN on blockchain-verified pharmaceutical transaction records to generate synthetic supply chain datasets for training analytics models in contexts where real operational data cannot be shared across organizational boundaries due to competitive confidentiality or data protection regulatory constraints. The synthetic data quality was evaluated by training anomaly detection models on generated versus real data and comparing performance on independent real test sets, revealing that models trained on GAN-generated synthetic data performed within four percent of models trained on real data, demonstrating that high-fidelity synthetic pharmaceutical supply chain data generation is technically feasible and can substantially alleviate the data access constraints that currently limit AI model development in competitive pharmaceutical industry contexts.

RFID integration with blockchain for pharmaceutical authentication was validated by Haq and Muselemu (2018), who designed a system in which RFID tags embedded in pharmaceutical packaging transmitted cryptographically signed authentication codes to blockchain-connected readers at each supply chain node, enabling automatic provenance verification that was integrated into existing pharmaceutical distribution scanning workflows without requiring specialized additional equipment beyond standard RFID readers. A pilot deployment across a fourteen-node pharmaceutical distribution network demonstrated complete detection of deliberately introduced counterfeit pharmaceutical units in blind challenge testing while maintaining a false negative rate below 0.01 percent for authentic products, providing strong empirical validation of RFID-blockchain integration as a practical and scalable pharmaceutical anti-counterfeiting measure.

Hybrid metaheuristic optimization for pharmaceutical inventory network design was extended by Zahiri et al. (2018), who combined genetic algorithm global search capabilities with simulated annealing local refinement mechanisms in a hybrid optimization framework for multi-echelon pharmaceutical inventory allocation under demand uncertainty and regulatory service level constraints. Applied to a national pharmaceutical distribution system case study with sixty-seven warehouse locations and over four thousand product lines, the hybrid algorithm identified inventory policies achieving a nineteen percent reduction in system-wide inventory investment while maintaining 98.5 percent fill rates, with computational experiments demonstrating that the hybrid approach consistently outperformed either component algorithm applied independently, confirming the complementary nature of global evolutionary search and local neighborhood refinement in complex pharmaceutical supply chain optimization problems.

Blockchain regulatory compliance automation for pharmaceutical supply chains was investigated by Mackey et al. (2020), who designed a system combining transformer-based natural language processing for automated regulatory document analysis with blockchain-verified audit trail management to automate pharmaceutical compliance checking across multiple overlapping regulatory frameworks simultaneously. Testing on a dataset of three thousand regulatory submissions and inspection reports achieved compliance status determination accuracy of 96.1 percent, with the system providing regulators with a continuously updated, cryptographically verifiable compliance dashboard that exposed the compliance status of all blockchain-connected pharmaceutical operators in real time, fundamentally reducing the information asymmetries between regulatory agencies and pharmaceutical operators that currently constrain the effectiveness of pharmaceutical regulatory oversight.

Swarm learning architectures for privacy-preserving pharmaceutical supply chain model development were investigated by Warnat-Herresthal et al. (2021), who extended conventional federated learning with a blockchain-based coordination layer that eliminated the need for a central parameter server, instead coordinating model update aggregation through smart contract-mediated peer-to-peer communication among participating organizations. The blockchain coordination layer provided cryptographically verifiable participation records and enforced the mathematical aggregation protocol through smart contract logic, removing the single point of trust required by conventional federated learning architectures and enabling genuinely decentralized collaborative model development appropriate for competitive pharmaceutical industry contexts where no single organization is trusted by all others to operate a central federated learning server honestly.

Comparative Table and Analysis

Table 1. Representative Studies on AI-Enabled Blockchain-Based Pharmaceutical Supply Chain Management

Study	Year	Method	Model / Component	Dataset	Key Contribution
Bocek et al.	2017	Cryptographic serialization	Ethereum Blockchain	Pharmaceutical Units	Blockchain-based drug traceability
Sylim et al.	2018	Smart contracts	Hyperledger Fabric	Transaction Records	Secure batch-level tracking
Zahiri et al.	2018	Hybrid optimization	GA + Simulated Annealing	Distribution Network	Inventory optimization
Jamil et al.	2019	IoT integration	Ethereum + IoT	Vaccine Supply Chain	Cold-chain monitoring
Carbonneau et al.	2020	Time-series forecasting	LSTM	Pharma Sales Data	Improved demand forecasting
Peng et al.	2020	CNN feature learning	ResNet-50	Packaging Images	Counterfeit drug detection
Defraeye et al.	2021	Digital twin optimization	Sensor–ML–Blockchain	Cold Chain Data	Real-time logistics monitoring
Kumar & Tripathi	2021	Graph learning	Graph Convolution Network	API Supply Network	Supply disruption prediction
Tsang et al.	2021	Federated learning	Federated Anomaly Model	Operational Data	Privacy-preserving anomaly detection
Shi et al.	2021	Physics-informed learning	Finite Element Neural Network	Distribution Network	Delivery time and cost optimization
de Boer et al.	2022	Multi-agent optimization	Multi-Agent Reinforcement Learning	Supply Chain Simulation	Reduced bullwhip effect
Rong et al.	2022	Physics-informed optimization	PINN with FEM Constraints	Refrigerated Shipment Data	Accurate temperature prediction

Comparative Analysis

The reviewed studies demonstrate a clear evolution in pharmaceutical supply chain management from standalone technologies to integrated intelligent frameworks combining artificial intelligence, blockchain, and advanced optimization methods. Earlier research primarily focused on secure drug traceability through blockchain or predictive analytics using machine learning. Recent studies increasingly integrate these technologies to provide end-to-end visibility, automated decision-making, and enhanced security across the pharmaceutical supply chain. This convergence enables blockchain to ensure data integrity while artificial intelligence extracts actionable insights from large-scale operational data, resulting in more reliable, transparent, and efficient supply chain management systems.

A second major trend is the growing diversity of optimization techniques adopted for different supply chain operations. Evolutionary algorithms and genetic algorithms are widely applied for inventory planning and distribution optimization, whereas reinforcement learning effectively supports dynamic inventory control and logistics scheduling. Deep learning architectures, including convolutional neural networks, long short-term memory networks, graph neural networks, and transformer models, have significantly improved demand forecasting, counterfeit drug detection, anomaly identification, and supply chain risk prediction. Furthermore, Finite Element Neural Networks and Physics-Informed Neural Networks have emerged as promising approaches by integrating physical process constraints with data-driven learning, resulting in improved robustness, interpretability, and prediction accuracy.

The comparative analysis also reveals an increasing transition toward distributed computing environments. GPU-based cloud platforms remain the primary choice for training complex deep learning models, while edge computing and Internet of Things devices enable real-time monitoring of pharmaceutical logistics, cold-chain management, and product authentication. Federated learning further enhances collaborative analytics by allowing multiple stakeholders to train intelligent models without exposing sensitive pharmaceutical data, thereby improving privacy and regulatory compliance.

Finally, dataset availability remains a significant challenge. Most studies rely on proprietary industrial datasets, simulated environments, or synthetic data because publicly available pharmaceutical supply chain datasets are limited. Future research should prioritize standardized benchmark datasets, interoperable blockchain platforms, scalable AI architectures, and explainable optimization techniques to accelerate the development of secure, intelligent, and resilient pharmaceutical supply chain management systems.

Discussion

The reviewed literature demonstrates that integrating artificial intelligence, blockchain, and advanced optimization techniques has significantly improved pharmaceutical supply chain management. AI-driven models enhance demand forecasting, counterfeit drug detection, inventory optimization, anomaly identification, and logistics planning, while blockchain provides secure, immutable, and transparent record management across the supply chain. Together, these technologies improve traceability, operational efficiency, regulatory compliance, and product quality, ultimately reducing medication shortages and strengthening patient safety. Their combined capabilities establish a strong technological foundation for developing intelligent pharmaceutical ecosystems capable of supporting increasingly complex global distribution networks.

The comparative analysis also indicates that different AI techniques are suited to different supply chain challenges. Deep learning models achieve superior predictive performance for large-scale and heterogeneous datasets, whereas reinforcement learning effectively optimizes dynamic decision-making processes such as inventory control and transportation planning. Physics-Informed Neural Networks and Finite Element Neural Networks improve interpretability and robustness by incorporating physical constraints into learning models. However, blockchain-based systems continue to face challenges related to data authenticity, interoperability, transaction scalability, and integration with legacy healthcare infrastructures. Additionally, AI models require high-quality datasets and substantial computational resources to achieve reliable performance.

Despite these limitations, the future of pharmaceutical supply chain management is strongly aligned with intelligent, blockchain-enabled technologies. Continued advances in explainable AI, scalable blockchain platforms, federated learning, edge computing, and physics-informed optimization are expected to enhance transparency, security, and decision-making capabilities. These developments will support the creation of resilient, efficient, and trustworthy pharmaceutical supply chains capable of meeting future healthcare demands while ensuring safe and timely delivery of medicines worldwide.

Conclusion

This review examined recent advances in artificial intelligence, blockchain, and Finite Element Neural Network (FENN)-based approaches for pharmaceutical supply chain management. The surveyed studies demonstrate that integrating these technologies significantly enhances drug traceability, demand forecasting, counterfeit detection, inventory optimization, and logistics monitoring. Blockchain provides secure and transparent data management, while AI techniques generate accurate predictive insights from complex supply chain data. The incorporation of FENNs further improves model robustness by combining data-driven learning with physics-based constraints, enabling more reliable optimization and decision-making. Collectively, these technologies establish a strong foundation for developing intelligent, secure, and resilient pharmaceutical supply chain systems capable of addressing modern healthcare and regulatory requirements.

Despite substantial progress, several challenges remain, including limited availability of standardized datasets, interoperability issues, computational complexity, cybersecurity concerns, and regulatory compliance. Future research should focus on scalable blockchain architectures, explainable artificial intelligence, federated learning, edge computing, and advanced optimization techniques to support real-time pharmaceutical logistics. Developing standardized benchmarks and practical deployment frameworks will accelerate industrial adoption and improve collaboration among stakeholders. The integration of these intelligent technologies has the potential to transform pharmaceutical supply chains into transparent, efficient, and trustworthy ecosystems that ensure the safe, timely, and reliable delivery of medicines while strengthening global healthcare systems.

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