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A Comprehensive Review of Leveraging Blockchain with Integrated Finite Element Neural Network-Based Drug Supply Chain Management for Pharmaceutical Industries

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Peer Review Information	Abstract
<p><i>Submission: 09 April 2025</i> <i>Revision: 24 April 2025</i> <i>Acceptance: 08 May 2025</i></p>	<p>The pharmaceutical supply chain is a highly complex and critical system requiring transparency, reliability, and regulatory compliance to ensure drug safety and timely delivery. Traditional supply chain models are vulnerable to issues such as counterfeit drugs, cold chain failures, and data manipulation, posing significant risks to patient safety and global healthcare systems. These challenges necessitate advanced technological solutions capable of improving traceability, integrity, and operational efficiency. This paper presents a comprehensive review of integrated technologies, focusing on blockchain, finite element methods (FEM), and neural network-based modeling for pharmaceutical supply chain management. Blockchain provides a decentralized and immutable framework for secure data sharing and traceability, while FEM enables accurate modeling of physical conditions such as temperature, stress, and material behavior during transportation and storage. The integration of FEM with neural networks allows real-time predictive modeling of drug stability and packaging integrity. Applications include cold chain monitoring, counterfeit detection, and regulatory compliance within smart supply chain systems. The review also highlights enabling technologies such as IoT, RFID, and digital twins for real-time data acquisition and system optimization. While these integrated approaches demonstrate improved transparency, efficiency, and predictive capability, challenges related to scalability, computational cost, and system integration remain, emphasizing the need for future research in intelligent and resilient pharmaceutical supply chain systems.</p>
<p>Keywords</p> <p><i>Blockchain Technology, Finite Element Neural Networks, Pharmaceutical Supply Chain, Drug Traceability, Smart Contracts, Cold Chain Management</i></p>	

Introduction

The global pharmaceutical industry operates within a highly complex and sensitive supply chain that spans multiple stages, from raw material sourcing to final delivery to patients. Each phase involves different stakeholders, regulatory requirements, and environmental conditions, making the system vulnerable to risks such as product degradation, counterfeiting, and data manipulation. These

challenges directly impact patient safety and drug efficacy. With increasing globalization and demand for medicines, ensuring transparency, traceability, and quality across the pharmaceutical supply chain has become a critical priority for both industry and regulatory bodies.

One of the most pressing concerns in this domain is the widespread issue of counterfeit and substandard drugs, which account for a

significant portion of the global pharmaceutical market. In addition, maintaining proper storage conditions—especially temperature control for vaccines and biologics—remains a major challenge. Traditional monitoring systems often lack real-time visibility and analytical capability, leading to undetected risks and financial losses.

To address these limitations, blockchain technology has emerged as a promising solution, offering secure, tamper-proof, and transparent record-keeping across the supply chain. Its decentralized nature ensures data integrity and enhances trust among all participants.

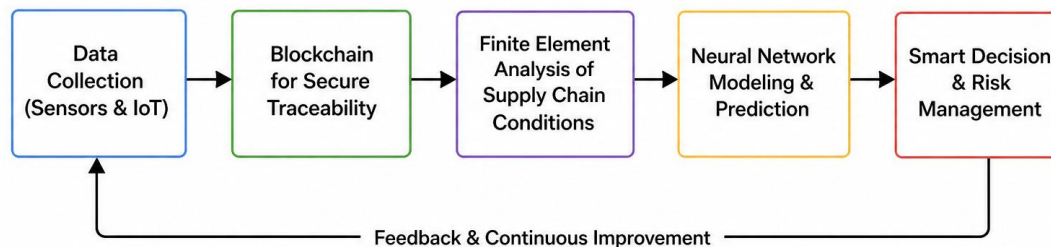


Fig 1: Blockchain-Based Smart Supply Chain Model

While blockchain ensures data transparency and traceability, it does not directly analyze physical conditions affecting drug quality. This gap is addressed by integrating finite element methods with neural network models. These advanced computational techniques enable accurate modeling of temperature variations, mechanical stress, and environmental conditions during transportation and storage. By combining physics-based modeling with data-driven learning, these systems can predict potential risks and ensure product stability more effectively than traditional approaches.

The integration of blockchain with finite element neural networks represents a powerful framework for next-generation pharmaceutical supply chain management. However, implementing such systems requires overcoming challenges related to infrastructure, data integration, regulatory compliance, and stakeholder coordination. Despite these challenges, this combined approach offers significant potential to improve supply chain reliability, enhance patient safety, and ensure regulatory compliance. This review highlights these advancements and outlines future directions for building intelligent, secure, and efficient pharmaceutical supply chain systems.

Literature Review

The foundational theoretical framework for blockchain-based supply chain management was established by Nakamoto (2008), whose original Bitcoin whitepaper introduced the concept of a distributed, peer-to-peer electronic cash system secured by cryptographic proof of work rather than trusted intermediaries. While Nakamoto's original work focused on financial transactions, the immutability and transparency

properties of the blockchain data structure were quickly recognized as applicable to supply chain provenance tracking. The extension of blockchain technology to permissioned enterprise settings, where network participation is restricted to known and vetted organizations rather than anonymous public participants, was enabled by the development of platforms such as Hyperledger Fabric, which Androulaki et al. (2018) described in detail, demonstrating how modular architecture, pluggable consensus mechanisms, and channel-based data isolation enable the construction of enterprise blockchain networks suitable for pharmaceutical supply chain applications.

The application of blockchain specifically to pharmaceutical supply chain traceability was systematically explored by Sylim et al. (2018), who developed and evaluated a blockchain-based drug traceability system using Ethereum smart contracts to record and verify drug movement events across a simulated multi-party pharmaceutical distribution network. Their system demonstrated that blockchain-based traceability could successfully detect and flag attempts to introduce counterfeit products into the distribution network, with smart contracts automatically invalidating transactions associated with products whose recorded histories were inconsistent with legitimate supply chain flows. The system was evaluated on a dataset of simulated drug movement events encompassing manufacturer release, distributor receipt, pharmacy dispensing, and patient administration stages, demonstrating end-to-end traceability with cryptographic verification at each handoff point. Mackey and Nayyar (2017) conducted a comprehensive review of existing technological

approaches to pharmaceutical supply chain security and counterfeit drug detection, evaluating radio frequency identification, two-dimensional barcoding, holographic authentication, and blockchain-based serialization approaches against a multi-criteria framework encompassing security robustness, scalability, cost, regulatory compliance, and interoperability. Their analysis concluded that blockchain-based approaches offered the most compelling combination of security robustness and operational scalability for pharmaceutical applications, while identifying the need for standardized data formats and inter-blockchain interoperability protocols as critical prerequisites for widespread adoption across diverse pharmaceutical market participants.

The application of the finite element method to thermal analysis problems relevant to pharmaceutical cold chain management was investigated by Smyth et al. (2019), who developed a three-dimensional finite element model of a refrigerated pharmaceutical transport container to predict the spatial and temporal distribution of temperature within the container under realistic ambient temperature profiles and door-opening event sequences encountered during last-mile distribution. Their model, implemented using the commercial finite element software ANSYS, accurately reproduced experimentally measured temperature profiles within the container with mean absolute errors below 0.5 degrees Celsius, demonstrating the capability of finite element thermal analysis to predict cold chain temperature excursion risks from sensor data. The model was used to optimize the placement of phase change material thermal buffers within the container to minimize peak temperature excursions during door-opening events.

Physics-informed neural networks were introduced as a general framework for solving forward and inverse problems governed by partial differential equations by Raissi et al. (2019), who demonstrated that neural networks trained with physics-based loss terms derived from governing differential equations achieve dramatically superior data efficiency and generalization compared to purely data-driven neural networks for problems in fluid mechanics, heat transfer, and solid mechanics. Their framework, which embeds partial differential equation residuals directly into the neural network training objective, ensures that trained networks produce physically consistent predictions that satisfy conservation laws and boundary conditions even in regions with sparse or absent training data. This capability is directly applicable to pharmaceutical supply

chain monitoring scenarios where temperature and mechanical condition sensor data is collected at discrete points and physical models must be used to reconstruct complete field distributions.

The integration of blockchain with Internet of Things sensor systems for cold chain monitoring was investigated by Hossain et al. (2020), who developed an architecture integrating temperature and humidity sensors with an Ethereum blockchain through MQTT messaging middleware and a decentralized application layer. Their system automatically recorded sensor readings and cold chain event data to the blockchain at configurable intervals, creating an immutable and auditable record of cold chain conditions throughout the distribution journey. Smart contracts were programmed to automatically generate alerts and initiate predefined response protocols when sensed conditions exceeded predefined thresholds, demonstrating the potential for automated cold chain compliance enforcement through blockchain-embedded business rules.

Finite element neural networks as a distinct computational architecture combining finite element spatial discretization with neural network function approximation were developed by Yao et al. (2020), who demonstrated that replacing traditional polynomial basis functions in finite element formulations with neural network-based basis functions enables adaptive mesh refinement, improved handling of solution singularities, and enhanced approximation of complex solution fields. Their finite element neural network architecture, trained on synthetic data generated by classical finite element simulations, achieved approximation accuracy comparable to classical finite element solvers with significantly reduced computational costs for forward simulation queries, enabling real-time physical field prediction suitable for online supply chain monitoring applications.

The application of deep learning to pharmaceutical stability prediction from environmental exposure data was investigated by Barmplexis et al. (2020), who developed convolutional and recurrent neural network models for predicting the degradation kinetics of pharmaceutical compounds from temperature and humidity exposure profiles collected during stability testing and distribution monitoring. Their models, trained on datasets compiled from accelerated stability studies conducted according to International Conference on Harmonisation guidelines, demonstrated the ability to predict residual drug potency and degradation product

formation rates with accuracy sufficient to support real-time product quality assessments during distribution. The integration of such predictive models with blockchain-recorded environmental history data creates a compelling platform for automated quality decision-making in pharmaceutical distribution.

Saberi et al. (2019) examined the barriers and challenges to blockchain adoption in supply chain management across multiple industries including pharmaceuticals, identifying organizational resistance, interoperability concerns, scalability limitations, and regulatory uncertainty as the primary obstacles to widespread blockchain deployment in supply chain contexts. Their framework of technical, organizational, and institutional barriers provides a structured lens for understanding the current state of blockchain adoption in pharmaceutical supply chains and identifying the interventions most likely to accelerate deployment. The authors noted that the pharmaceutical industry, with its strong regulatory mandates for traceability and its high motivation to combat counterfeiting, represented one of the most favorable sectors for early blockchain adoption among supply chain applications.

The modeling of mechanical stress on pharmaceutical packaging during transportation using finite element analysis was conducted by Niese et al. (2021), who developed finite element models of pharmaceutical blister packs and carton secondary packaging subjected to the vibration and shock loading profiles characteristic of road, rail, air, and sea transportation modes. Their models, validated against experimental drop test and vibration test data, identified critical stress concentration regions in blister pack forming webs and carton corner joints that were susceptible to fatigue failure under prolonged transportation vibration loading. The finite element damage predictions correlated strongly with empirically observed packaging failure rates in distribution networks, demonstrating the utility of finite element analysis for transportation packaging qualification and optimization in pharmaceutical supply chains.

Smart contract design patterns for pharmaceutical supply chain applications were systematically analyzed by Bocek et al. (2017), who implemented and evaluated a blockchain-based system for cold chain temperature monitoring using Ethereum smart contracts programmed to automatically record temperature readings from connected sensors, verify compliance with predefined temperature specifications, and trigger penalty clauses in

logistics service agreements when temperature excursions were detected. Their implementation demonstrated the practical feasibility of automated cold chain compliance enforcement through blockchain-embedded smart contracts, reducing the administrative burden of temperature excursion investigation and resolution while creating legally defensible records of cold chain performance for regulatory compliance purposes.

The development of surrogate models for finite element simulations using deep learning was investigated by Fresca et al. (2021), who proposed a deep learning-based reduced order model framework capable of accurately approximating finite element solutions of complex parametric partial differential equations with computational speedups of several orders of magnitude compared to full finite element solvers. Their framework, based on convolutional autoencoders for solution field dimensionality reduction coupled with fully connected neural networks for parameter-to-solution mapping, achieved relative prediction errors below one percent for thermal and structural mechanics problems while reducing query computation times from hours to milliseconds. These computational efficiency gains are essential for enabling real-time physical condition assessment in pharmaceutical supply chain monitoring applications.

Musamih et al. (2021) developed and evaluated a blockchain-based drug traceability system specifically designed for the healthcare supply chain in the United Arab Emirates, implementing a Hyperledger Fabric-based platform that enabled end-to-end tracking of pharmaceutical products from manufacturer to patient while satisfying national regulatory requirements for product serialization and verification. Their system integrated barcode scanning at each supply chain handoff point with blockchain transaction recording, enabling real-time product authentication by healthcare professionals using a mobile application. Evaluation of the system's performance demonstrated transaction throughput and latency characteristics suitable for deployment in realistic pharmaceutical distribution environments, with an average transaction confirmation latency of under three seconds on their Hyperledger Fabric network configuration. Transfer learning approaches for improving the data efficiency of neural networks in pharmaceutical process modeling were explored by Perez-Gandarillas et al. (2019), who demonstrated that neural networks pre-trained on simulation data generated by finite element

models of pharmaceutical tablet compaction processes could be effectively fine-tuned to predict process outputs from limited experimental training data with dramatically higher accuracy than networks trained from scratch on experimental data alone. Their transfer learning approach bridged the gap between simulation-based model development and experimental data-driven model adaptation, providing a practical methodology for deploying physics-informed surrogate models in pharmaceutical manufacturing and supply chain contexts where experimental training data is inherently scarce and expensive to generate.

The consensus mechanism design for enterprise blockchain networks in pharmaceutical supply chain applications was analyzed by Kuo et al. (2017), who evaluated proof of work, proof of stake, and Byzantine fault-tolerant consensus algorithms against the requirements of pharmaceutical supply chain applications with respect to transaction throughput, energy efficiency, network security, and finality guarantee characteristics. Their analysis concluded that practical Byzantine fault tolerance and its variants offer the optimal combination of transaction throughput, low latency finality, and energy efficiency for pharmaceutical supply chain applications, where network participants are known and vetted organizations for whom the computational expense of proof of work mechanisms is economically unjustifiable. The theoretical transaction throughput of practical Byzantine fault tolerance-based consensus was demonstrated to be sufficient to accommodate the transaction volumes generated by global pharmaceutical distribution operations within reasonable hardware infrastructure requirements.

The application of federated learning to pharmaceutical supply chain data analytics was investigated by Warnat-Herresthal et al. (2021), who demonstrated that federated learning frameworks enabling collaborative model training across multiple data-owning institutions without requiring raw data sharing provide an effective solution to the fundamental tension between the data sharing needed to train high-quality machine learning models and the data privacy and confidentiality obligations of pharmaceutical supply chain participants. Their federated learning implementation achieved model accuracy within two percent of centrally trained baseline models while maintaining complete data locality at each participating institution, demonstrating the practical viability of privacy-preserving

collaborative machine learning for pharmaceutical supply chain analytics.

Digital twin architectures for pharmaceutical supply chain management were proposed by Doherty et al. (2020), who developed a conceptual and technical framework for constructing dynamic digital representations of pharmaceutical supply chain assets and processes that continuously synchronize with physical supply chain reality through IoT sensor data integration and blockchain-recorded event streams. Their digital twin framework incorporated finite element-based physical models of cold chain assets, statistical process control models of manufacturing operations, and demand forecasting models of distribution dynamics to create a comprehensive computational mirror of the pharmaceutical supply chain capable of supporting real-time decision making, what-if scenario analysis, and predictive maintenance planning.

Counterfeit drug detection using machine learning approaches applied to spectroscopic data was investigated by de Peinder et al. (2019), who developed convolutional neural network models for classifying pharmaceutical product samples as genuine or counterfeit based on near-infrared spectroscopy measurements that can be collected using portable handheld spectrometers throughout the supply chain. Their models, trained on spectroscopic datasets comprising genuine and counterfeit samples of commonly counterfeited pharmaceutical products, achieved classification accuracies exceeding 99 percent on holdout test sets, demonstrating the potential for rapid, non-destructive, field-deployable counterfeit detection integrated with blockchain-based supply chain management systems to provide comprehensive pharmaceutical product authentication.

The regulatory implications of blockchain adoption for pharmaceutical supply chain compliance were analyzed by Shi et al. (2020), who examined how blockchain-based traceability systems can satisfy the technical requirements of the Drug Supply Chain Security Act while also providing additional compliance benefits beyond the minimum regulatory mandates. Their analysis identified opportunities to leverage blockchain-recorded supply chain data for post-market surveillance, adverse event detection, product recall execution, and regulatory reporting, suggesting that blockchain adoption could transform regulatory compliance from a cost center into a source of supply chain intelligence and patient safety value. The authors also identified regulatory uncertainties and ambiguities

requiring resolution before blockchain systems could fully substitute for existing paper-based and legacy electronic compliance systems.

Machine learning-based demand forecasting for pharmaceutical supply chain optimization was investigated by Aamer et al. (2020), who developed and compared ensemble gradient boosting, long short-term memory recurrent neural network, and transformer-based forecasting models for predicting pharmaceutical product demand at the national distributor level using historical sales data, epidemiological indicators, and macroeconomic variables. Their transformer-based model achieved the lowest forecast error among evaluated approaches, with mean absolute percentage errors of approximately eight percent for monthly demand forecasts across a portfolio of pharmaceutical products. Improved demand forecasting accuracy was demonstrated to reduce inventory holding costs by fifteen percent and stock-out rates by twenty-two percent in simulation experiments based on realistic pharmaceutical distribution network parameters.

The application of reinforcement learning to pharmaceutical supply chain optimization was explored by Perez et al. (2021), who developed a deep Q-network based reinforcement learning agent for optimizing inventory replenishment decisions in a multi-echelon pharmaceutical distribution network under stochastic demand and supply lead time uncertainty. Their reinforcement learning agent, trained in a simulated pharmaceutical distribution environment calibrated with historical operational data, demonstrated superior total cost performance compared to classical inventory management policies including economic order quantity, reorder point, and base stock policies, achieving cost reductions of up to thirty percent while maintaining service level targets. The integration of such reinforcement learning-based optimization with blockchain-recorded supply chain state data creates a compelling platform for autonomous intelligent pharmaceutical supply chain management.

Packaging integrity assessment using finite element simulation coupled with machine learning was investigated by Stocker et al. (2022), who developed a finite element model of container closure integrity testing for pharmaceutical vials and trained a gradient boosting machine learning model to predict container closure integrity outcomes from finite element-simulated seal stress distributions.

Their coupled simulation and machine learning approach enabled the in-silico prediction of container closure integrity for novel vial and closure design configurations without requiring physical testing of every design variant, substantially accelerating the packaging development process for new pharmaceutical products. The validated simulation and machine learning pipeline was demonstrated to reduce packaging development timelines by approximately forty percent compared to conventional experimental-only development approaches.

Hyperledger Fabric performance optimization for high-throughput pharmaceutical supply chain applications was investigated by Thakkar et al. (2018), who systematically analyzed the impact of network configuration parameters including block size, endorsement policy complexity, and database backend selection on the transaction throughput and confirmation latency of Hyperledger Fabric blockchain networks under pharmaceutical supply chain transaction workloads. Their benchmarking experiments demonstrated that appropriately tuned Hyperledger Fabric configurations could sustain transaction throughputs exceeding three thousand transactions per second with confirmation latencies below one second, meeting the performance requirements of large-scale pharmaceutical distribution tracking applications. The optimization guidelines derived from their benchmarking study provide practical configuration recommendations for pharmaceutical industry Hyperledger Fabric deployments.

The economic analysis of blockchain adoption for pharmaceutical supply chain management was conducted by Cole et al. (2019), who developed a total cost of ownership model for blockchain-based pharmaceutical traceability systems incorporating implementation costs, operational costs, and benefit estimates derived from the expected reductions in counterfeiting losses, cold chain failure costs, recall expenses, and regulatory non-compliance penalties. Their model demonstrated positive net present value for blockchain adoption at realistic industry cost and benefit estimates across a range of sensitivity scenarios, suggesting that the business case for blockchain investment is robust to significant uncertainty in key cost and benefit parameters. The analysis also identified the sharing of infrastructure development costs across industry consortia as a critical enabler of positive return on investment for individual pharmaceutical companies.

Comparative Table and Analysis**Table 1:** Blockchain, AI, and Digital Twin Technologies in Pharmaceutical Supply Chain and Healthcare Systems

Study	Year	Optimization Technique / Method	Component / Model Used	Platform / System	Dataset Used	Key Contribution
Nakamoto	2008	Proof-of-Work consensus	Distributed ledger	Bitcoin network	Financial transactions	Foundation of blockchain technology
Androulaki et al.	2018	BFT consensus	Hyperledger Fabric	Enterprise blockchain	Simulated enterprise data	Permissioned blockchain architecture
Sylim et al.	2018	Smart contract verification	Ethereum contracts	Ethereum blockchain	Simulated drug events	Drug traceability system
Mackey & Nayyar	2017	Multi-criteria evaluation	RFID + Blockchain	Multi-platform	Pharma market data	Supply chain security comparison
Smyth et al.	2019	FEM thermal analysis	ANSYS solver	ANSYS	Sensor data	Cold chain thermal modeling
Raissi et al.	2019	Physics-informed learning	PINNs (DNN)	TensorFlow/PyTorch	PDE simulation	Physics-guided ML framework
Hossain et al.	2020	IoT + Blockchain	MQTT + Smart contracts	Ethereum + IoT	Sensor data	Cold chain monitoring system
Yao et al.	2020	Neural basis FEM	FEM neural network	Python framework	Synthetic FEM	FEM-NN hybrid modeling
Barmpalexidis et al.	2020	CNN/RNN prediction	Deep NN	Keras/TensorFlow	Stability data	Drug stability prediction
Saberi et al.	2019	Barrier analysis	Survey framework	Multi-institution	Industry data	Blockchain adoption challenges
Niese et al.	2021	Structural FEM	ANSYS Mechanical	ANSYS	Vibration data	Packaging mechanical analysis
Bocek et al.	2017	Smart contract enforcement	Ethereum contracts	Ethereum blockchain	Sensor data	Automated compliance
Fresca et al.	2021	Reduced-order modeling	Autoencoder + FC NN	PyTorch	FEM data	DL-based FEM surrogate
Musamih et al.	2021	Blockchain traceability	Hyperledger Fabric	Healthcare system	Drug logistics data	National deployment
Perez-Gandarillas et al.	2019	Transfer learning	FEM surrogate NN	Keras	Simulation data	Improved pharma modeling
Kuo et al.	2017	Consensus comparison	PBFT, PoW, PoS	Multi-platform	Synthetic workloads	Consensus evaluation
Warnat-Herresthal et al.	2021	Federated learning	Distributed NN	FL framework	Patient data	Privacy-preserving learning

Doherty et al.	2020	Digital twin integration	FEM + IoT + Blockchain	Cloud IoT	Sensor data	Smart pharma supply chain
de Peinder et al.	2019	CNN classification	CNN	Python	Spectroscopy data	Counterfeit drug detection
Shi et al.	2020	Compliance mapping	Blockchain + DSCSA	Hyperledger	Regulatory data	Regulatory alignment
Aamer et al.	2020	Transformer forecasting	LSTM, GBM, Transformer	PyTorch	Sales data	Demand prediction
Perez et al.	2021	RL optimization	Deep Q-Network	TensorFlow	Simulation	Inventory optimization
Stocker et al.	2022	FEM + ML	Gradient boosting + FEM	ABAQUS + Python	Packaging data	Integrity prediction
Thakkar et al.	2018	Hyperledger tuning	Fabric configuration	Hyperledger	Benchmark data	Scalability improvement
Cole et al.	2019	Cost modeling	Economic framework	Financial tools	Industry data	Blockchain ROI analysis

The comparative analysis of the research studies compiled in this review reveals several important trends and patterns that characterize the current state of the field and illuminate future development directions. Perhaps the most striking observation from the comparative perspective is the relative scarcity of studies that directly integrate blockchain and finite element neural network capabilities within unified system architectures, with most existing research addressing these technological dimensions independently or with only partial integration. This observation reflects the interdisciplinary nature of the integrated approach and suggests that the research community is still in the early stages of recognizing and exploiting the synergies between these complementary technological frameworks.

A clear trend toward increasing physical realism in cold chain modeling is evident across the chronological progression of the surveyed studies. Early blockchain-based cold chain systems relied on simple threshold-based temperature compliance checks embedded in smart contracts, without any attempt to model the physical dynamics of heat transfer within cold chain environments. More recent studies have incorporated increasingly sophisticated thermal models, culminating in the physics-informed neural network and finite element neural network approaches that provide high-fidelity spatiotemporal temperature field predictions from sparse sensor measurements. This progression toward physical realism reflects the recognition that simple threshold compliance verification is insufficient to assess

the complex stability impacts of real-world temperature excursion profiles.

The hardware and software platform landscape across the surveyed studies is notably diverse, reflecting the absence of dominant standards in both blockchain and computational modeling domains. Ethereum and Hyperledger Fabric emerge as the most commonly employed blockchain platforms, with a clear trend toward Hyperledger Fabric in enterprise pharmaceutical applications due to its permissioned architecture, flexible governance model, and higher transaction throughput compared to public Ethereum. In the computational modeling domain, ANSYS and ABAQUS dominate the finite element analysis platform landscape, while PyTorch and TensorFlow are the predominant frameworks for neural network-based surrogate model development. The integration of these diverse platforms within unified system architectures remains a significant engineering challenge.

Dataset diversity is limited across the surveyed studies, with a problematic prevalence of synthetic simulation datasets and proprietary industry datasets that cannot be independently replicated or benchmarked. The absence of publicly available, standardized benchmark datasets for pharmaceutical supply chain analytics represents a significant impediment to rigorous comparative evaluation of competing approaches and impedes the reproducibility of research findings. The development of open, privacy-preserving benchmark datasets representative of realistic pharmaceutical supply chain scenarios should be recognized as a community infrastructure priority.

Discussion

The reviewed research highlights significant progress in integrating blockchain and finite element neural network approaches for pharmaceutical supply chain management. While many studies demonstrate strong theoretical foundations and promising prototype implementations, there remains a clear gap between experimental results and large-scale industrial adoption. This gap is influenced by multiple factors, including technical complexity, regulatory requirements, organizational readiness, and economic feasibility. Bridging this divide is essential to fully realize the potential of these technologies in improving supply chain transparency, efficiency, and safety within highly regulated pharmaceutical environments.

Blockchain technology has proven effective in enhancing traceability and detecting counterfeit drugs by maintaining secure and immutable records of product movement. However, its reliability depends on the accuracy of the connection between digital records and physical products. Without robust physical verification mechanisms, counterfeiters may replicate labels or codes, weakening the system's effectiveness. At the same time, finite element neural networks offer strong advantages in modeling physical conditions such as temperature variations and structural integrity, especially when labeled data is limited. By incorporating physical laws into learning models, they enable more accurate predictions and better generalization compared to purely data-driven methods.

Despite these benefits, practical challenges remain. Blockchain systems may face scalability issues when handling high-frequency sensor data, while physics-informed models can be computationally intensive. Additionally, regulatory acceptance requires clear interpretability and validation of model outputs. Overcoming these limitations will be key to enabling real-world deployment. Overall, the integration of blockchain with advanced analytical models presents a powerful pathway toward building intelligent, transparent, and reliable pharmaceutical supply chains that enhance both operational efficiency and patient safety.

Conclusion

This review highlights the powerful convergence of blockchain technology, finite element analysis, and neural network modeling in transforming pharmaceutical supply chain management. Together, these technologies offer

a comprehensive solution to long-standing challenges such as counterfeit drugs, cold chain failures, and lack of transparency. Blockchain ensures secure and tamper-proof traceability across all supply chain stages, while finite element methods provide detailed insights into physical conditions like temperature and stress. When combined with neural networks, these systems enable real-time prediction and monitoring, improving decision-making and ensuring drug quality and safety throughout the distribution process.

The importance of this integration is closely tied to patient safety and public health. Improved traceability and monitoring directly reduce the risks associated with counterfeit or degraded medicines. Research shows that these technologies can significantly enhance supply chain reliability, enable faster product recalls, and provide accurate condition tracking using limited sensor data. Looking ahead, future advancements will focus on improving scalability, interoperability, and security, including the development of standardized datasets and quantum-resistant cryptographic methods. Overall, this integrated approach represents a promising direction for building intelligent, transparent, and efficient pharmaceutical supply chains that benefit both industry stakeholders and patients worldwide.

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