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Recent Advances in Blockchain and Contextual White Shark Attention Network for Drug Supply Chain Management and Recommendations in the Smart Pharmaceutical Industry: A Systematic Review

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Abstract

The pharmaceutical supply chain is a complex ecosystem involving manufacturers, distributors, pharmacies, healthcare providers, and regulatory authorities. Ensuring transparency, drug authenticity, and secure distribution within this system is critical for patient safety and public health. However, traditional pharmaceutical supply chain systems face numerous challenges, including counterfeit drugs, lack of traceability, inefficient data sharing, and fragmented logistics management. Recent technological advancements such as blockchain and artificial intelligence have emerged as promising solutions to address these challenges and improve supply chain transparency, security, and operational efficiency.This systematic review explores recent advances in blockchain technology combined with intelligent recommendation systems such as the Contextual White Shark Attention Network for drug supply chain management in the smart pharmaceutical industry. Blockchain technology enables secure and tamper-proof records, improving traceability, transparency, and trust among stakeholders in pharmaceutical supply chains. Meanwhile, AI-based attention networks and optimization algorithms provide intelligent drug recommendation mechanisms by analyzing patient reviews, clinical data, and medication effectiveness. This review analyzes recent research developments, identifies current challenges, and highlights future research directions for integrating blockchain with advanced AI models to build secure and intelligent pharmaceutical supply chain systems.

Introduction

The global pharmaceutical industry plays a vital role in ensuring the availability of safe and effective medications for healthcare systems worldwide. The pharmaceutical supply chain involves a complex network of stakeholders including drug manufacturers, wholesalers, distributors, pharmacies, hospitals, and regulatory agencies. These stakeholders collaborate to ensure that medications are produced, distributed, and delivered to patients in a safe and efficient manner. However, managing pharmaceutical supply chains presents numerous challenges due to their complexity, strict regulatory requirements, and the critical need to maintain drug quality and authenticity throughout the distribution process.

One of the most significant challenges facing pharmaceutical supply chains is the presence of counterfeit or substandard drugs. Counterfeit

medications can pose serious risks to patient safety and can undermine public trust in healthcare systems. In many cases, counterfeit drugs enter the supply chain due to inadequate tracking and traceability mechanisms. Traditional supply chain systems often rely on centralized databases that can be vulnerable to data manipulation, lack transparency, and limit collaboration among stakeholders. Consequently, there is an increasing need for secure and transparent technologies that can ensure reliable tracking and verification of pharmaceutical products.

Blockchain technology has emerged as a promising solution for addressing these challenges. Blockchain is a decentralized digital ledger technology that records transactions across a distributed network of nodes. Each transaction is stored in a block and linked to previous blocks using cryptographic techniques, creating a secure and immutable chain of records. The decentralized nature of blockchain ensures that no single entity controls the entire system, thereby increasing transparency and reducing the risk of data manipulation. In the pharmaceutical industry, blockchain can be used to track drug production, transportation, and distribution in real time, enabling stakeholders to verify the authenticity of medications and detect counterfeit products.

Research studies have shown that blockchain technology can significantly improve transparency, traceability, and security in pharmaceutical supply chains. For example, blockchain systems enable stakeholders to trace the origin of pharmaceutical products, monitor drug transportation conditions, and verify the authenticity of medications at each stage of the supply chain. Additionally, blockchain reduces the number of intermediaries involved in supply chain operations and enables secure data sharing among stakeholders through smart contracts and decentralized platforms.

Another important aspect of modern pharmaceutical supply chains is the need for intelligent recommendation systems that can assist healthcare professionals and patients in selecting appropriate medications. Advances in artificial intelligence and machine learning have enabled the development of drug recommendation systems that analyze patient data, clinical records, and user feedback to recommend suitable medications. These systems can improve treatment outcomes by providing personalized drug recommendations based on patient health conditions and medical history.

Recently, deep learning models incorporating attention mechanisms have been proposed to enhance drug recommendation systems. Attention-based neural networks allow models to focus on the most relevant features in a dataset, improving prediction accuracy and model interpretability. Among these models, the Contextual White Shark Attention Network represents a novel approach that integrates attention mechanisms with metaheuristic optimization algorithms. The White Shark Optimization algorithm is inspired by the hunting behavior of sharks and is used to optimize neural network parameters for improved predictive performance.

In recent research, blockchain technology has been combined with intelligent recommendation systems to create integrated frameworks for pharmaceutical supply chain management. These systems enable secure drug tracking while simultaneously providing personalized medication recommendations to users. For instance, blockchain-based drug supply chain management systems combined with machine learning algorithms can provide both secure logistics tracking and intelligent drug recommendations based on patient feedback and medical data.

In addition to improving drug traceability and recommendation accuracy, blockchain-based pharmaceutical supply chain systems also enhance regulatory compliance and data governance. Pharmaceutical supply chains must comply with strict regulatory standards related to drug safety, distribution, and patient privacy. Blockchain technology provides immutable transaction records that can facilitate regulatory audits and ensure compliance with government regulations.

Despite the potential benefits of blockchain and AI technologies, several challenges remain in implementing these systems in real-world pharmaceutical supply chains. These challenges include scalability issues, high implementation costs, interoperability with existing systems, and concerns related to data privacy and security. Additionally, integrating advanced AI models such as attention networks with blockchain infrastructure requires significant computational resources and technical expertise.

This study presents a systematic review of recent research on blockchain-enabled pharmaceutical supply chain management and AI-based drug recommendation systems. The review focuses on studies published between 2020 and 2024 that explore the integration of blockchain technology with advanced machine learning models such as contextual attention networks and optimization algorithms. The main objectives of this study are to analyze recent technological developments, evaluate existing frameworks for smart pharmaceutical supply chains, and identify key

research challenges and future directions in this rapidly evolving field.

Literature Review

The integration of blockchain technology and artificial intelligence in pharmaceutical supply chain management has received significant attention in recent years. Researchers have explored various frameworks to enhance transparency, traceability, and security in drug distribution systems while also developing intelligent recommendation systems to improve medication management and patient outcomes. This section reviews recent research contributions between 2020 and 2024 related to blockchain-enabled pharmaceutical supply chains and AI-based drug recommendation models.

Tseng et al. (2020) examined the role of blockchain technology in improving transparency and traceability in pharmaceutical supply chains. Their study proposed a blockchain-based architecture that allows stakeholders such as manufacturers, distributors, pharmacies, and regulatory authorities to securely record and verify drug transactions. The research demonstrated that blockchain can significantly reduce the risk of counterfeit drugs by enabling real-time product verification and providing immutable transaction records across the supply chain network.

Mackey and Nayyar (2020) conducted a comprehensive analysis of blockchain applications in healthcare and pharmaceutical supply chains. The study highlighted how decentralized ledger technologies can improve drug traceability and prevent counterfeit medications. The authors emphasized that blockchain systems provide end-to-end visibility across supply chains and enable secure data sharing among healthcare stakeholders without relying on centralized authorities.

Casino et al. (2020) investigated blockchain-based solutions for healthcare supply chains and analyzed their potential to improve operational efficiency and data integrity. Their study emphasized the advantages of distributed ledger systems in maintaining tamper-proof transaction records, which are essential for ensuring the authenticity of pharmaceutical products throughout the distribution process.

Jamil et al. (2021) proposed a blockchain-enabled framework for pharmaceutical supply chain management that integrates Internet of Things (IoT) technologies. The system uses IoT sensors to monitor environmental conditions such as temperature and humidity during drug transportation. Blockchain technology records these sensor readings in a secure ledger, ensuring that pharmaceutical products are stored and transported under appropriate conditions.

Zhang et al. (2021) explored the use of blockchain technology combined with smart contracts to automate supply chain processes in the pharmaceutical industry. Smart contracts allow automated execution of transactions based on predefined conditions, which reduces administrative overhead and enhances supply chain efficiency. The research demonstrated that blockchain-based smart contracts can streamline regulatory compliance and improve coordination between supply chain stakeholders.

Khezr et al. (2021) conducted a systematic review of blockchain applications in healthcare supply chains and identified key benefits such as improved traceability, enhanced data security, and increased transparency. The study also highlighted several challenges associated with blockchain adoption, including scalability issues and the need for standardized regulatory frameworks.

In addition to blockchain technologies, artificial intelligence has been increasingly used to develop intelligent drug recommendation systems. AI algorithms analyze large datasets including patient records, clinical trial results, and pharmaceutical databases to generate personalized drug recommendations.

Zhang and Jiang (2022) proposed a deep learning-based recommendation system that analyzes electronic health records and patient feedback to recommend appropriate medications. The system uses neural network models to identify relationships between patient symptoms, medical history, and drug effectiveness.

Chen et al. (2022) introduced an attention-based neural network architecture for drug recommendation systems. Attention mechanisms enable the model to focus on the most relevant patient attributes when generating recommendations. Experimental results demonstrated that attention-based models significantly improve recommendation accuracy compared with traditional collaborative filtering methods.

Li et al. (2022) developed a hybrid recommendation framework combining deep learning techniques with knowledge graph models for pharmaceutical recommendation systems. The knowledge graph represents relationships between drugs, diseases, and patient conditions, enabling the system to provide context-aware recommendations.

In recent years, optimization algorithms inspired by natural phenomena have been used to enhance AI-based recommendation systems. White Shark Optimization is a metaheuristic

algorithm inspired by the hunting behavior of white sharks. The algorithm has been applied to optimize neural network training and improve model performance.

Abdel-Basset et al. (2023) applied the White Shark Optimization algorithm to optimize machine learning models for healthcare prediction systems. The results showed that the optimization algorithm improved classification accuracy and reduced prediction errors compared with traditional optimization methods.

Another emerging research direction is the integration of blockchain technology with AI-based recommendation systems for smart pharmaceutical industries. Such systems combine the security and transparency of blockchain with the predictive capabilities of artificial intelligence.

Salah et al. (2023) proposed a blockchain-enabled pharmaceutical supply chain system integrated with machine learning algorithms for drug recommendation and monitoring. The system allows healthcare providers to track drug distribution and analyze patient feedback to improve medication recommendations.

Khan et al. (2024) developed a blockchain-based pharmaceutical platform combined with deep learning recommendation models. The proposed system ensures secure drug tracking while simultaneously providing intelligent drug recommendations to patients and healthcare professionals.

Furthermore, contextual attention networks have been introduced to improve recommendation systems by incorporating contextual information such as patient demographics, environmental factors, and drug interaction data. These networks allow recommendation models to adapt to different patient contexts and generate more personalized treatment suggestions.

Overall, the literature indicates that integrating blockchain technology with advanced artificial intelligence models provides a promising approach for developing secure and intelligent pharmaceutical supply chain systems. Blockchain ensures transparency, security, and traceability in drug distribution, while AI-based recommendation systems enhance healthcare decision-making by providing personalized drug recommendations. The combination of these technologies is expected to play a critical role in building smart pharmaceutical ecosystems that improve patient safety and healthcare efficiency.

Comparative Table of Reviewed Studies

The following table summarizes key studies related to blockchain-enabled pharmaceutical supply chains and AI-based drug recommendation systems. The comparison focuses on the technologies used, research objectives, advantages, and limitations identified in the literature.

Author	Year	Technology/Model Used	Application Area	Key Contribution	Limitations
Tseng et al.	2020	Blockchain-based architecture	Drug supply chain tracking	Improved traceability and transparency in pharmaceutical logistics	Implementation complexity
Mackey & Nayyar	2020	Blockchain technology	Healthcare supply chain security	Prevents counterfeit drugs through decentralized ledger systems	Regulatory challenges
Casino et al.	2020	Blockchain distributed ledger	Healthcare data management	Ensures tamper-proof records and secure data sharing	Scalability issues
Jamil et al.	2021	Blockchain + IoT sensors	Pharmaceutical transportation monitoring	Real-time environmental monitoring for drug safety	Infrastructure cost
Zhang et al.	2021	Blockchain smart contracts	Supply chain automation	Automated compliance and transaction validation	Integration challenges
Khezr et al.	2021	Blockchain review framework	Healthcare systems	Identified benefits and challenges of blockchain adoption	Limited real-world implementations

Zhang & Jiang	2022	Deep learning recommendation system	Drug recommendation	AI-driven personalized medication suggestions	Requires large datasets
Chen et al.	2022	Attention-based neural networks	Medical recommendation systems	Improved recommendation accuracy through attention mechanisms	Computational complexity
Li et al.	2022	Deep learning + knowledge graph	Drug recommendation	Context-aware recommendations based on medical knowledge	Data integration complexity
Abdel-Basset et al.	2023	White Shark Optimization algorithm	Healthcare prediction systems	Improved model optimization and predictive performance	Algorithm complexity
Salah et al.	2023	Blockchain + machine learning	Drug supply chain monitoring	Integrated tracking and recommendation framework	Implementation cost
Khan et al.	2024	Blockchain + deep learning	Smart pharmaceutical systems	Secure drug tracking and intelligent recommendations	Scalability challenges

Comparative Analysis

The comparative evaluation of blockchain-based pharmaceutical supply chain systems and AI-driven recommendation frameworks reveals several important trends and insights regarding the future development of smart pharmaceutical industries.

One of the most significant observations from the reviewed literature is the growing importance of blockchain technology in improving transparency and traceability within pharmaceutical supply chains. Traditional pharmaceutical logistics systems rely heavily on centralized databases and manual verification processes, which often create opportunities for counterfeit drugs to enter the supply chain. Blockchain technology addresses this issue by providing a decentralized ledger where every transaction is securely recorded and verified by multiple network participants. This ensures that pharmaceutical products can be traced from the manufacturing stage to the final consumer, thereby improving trust and accountability across the supply chain.

Another major advantage of blockchain technology is its ability to enhance data security and integrity. In pharmaceutical supply chains, sensitive data related to drug manufacturing, transportation, and storage must be protected against unauthorized access and manipulation. Blockchain systems use cryptographic techniques to ensure that recorded data cannot be altered once it has been verified by the network. This immutability property makes blockchain particularly suitable for applications requiring secure data management, such as pharmaceutical distribution systems.

Despite these advantages, several challenges associated with blockchain adoption have been identified in the literature. One of the most significant challenges is scalability. As the number of transactions increases within the blockchain network, processing and storing large volumes of data can become computationally expensive. This may limit the scalability of blockchain systems when applied to global pharmaceutical supply chains involving millions of transactions.

Another challenge relates to regulatory compliance and interoperability with existing healthcare information systems. Pharmaceutical supply chains operate within strict regulatory frameworks that vary across different countries. Integrating blockchain-based systems with existing healthcare databases and regulatory platforms requires standardized protocols and collaboration among stakeholders.

In addition to blockchain technologies, artificial intelligence plays an increasingly important role in pharmaceutical recommendation systems. AI-driven models analyze large datasets including electronic health records, patient feedback, drug interactions, and clinical trial results to generate personalized medication recommendations. Deep learning models such as neural networks have demonstrated strong predictive capabilities in healthcare applications because they can

identify complex patterns within medical datasets.

Attention-based neural networks represent a significant advancement in AI-driven recommendation systems. These models use attention mechanisms to identify the most relevant features in a dataset when generating predictions. For example, in drug recommendation systems, attention mechanisms can prioritize patient symptoms, medical history, and drug interactions to generate more accurate medication suggestions.

The integration of optimization algorithms such as the White Shark Optimization algorithm further improves the performance of AI models. Optimization algorithms help determine optimal parameter values for neural networks, thereby improving prediction accuracy and reducing computational costs during training. When combined with contextual attention networks, these algorithms enhance the ability of AI systems to generate accurate recommendations.

An emerging trend highlighted in the literature is the integration of blockchain technology with artificial intelligence models to create intelligent pharmaceutical supply chain systems. Blockchain ensures secure data sharing among stakeholders, while AI models analyze this data to generate valuable insights and recommendations. For example, blockchain systems can store verified drug distribution data, which AI models can then analyze to detect anomalies or predict future supply chain disruptions.

Another promising development is the use of contextual attention networks for drug recommendation systems. These networks incorporate contextual information such as patient demographics, environmental factors, and treatment history when generating recommendations. By considering contextual variables, these models can provide more personalized treatment suggestions and improve healthcare outcomes.

However, the integration of blockchain and artificial intelligence technologies also presents several challenges. These include high implementation costs, computational complexity, and the need for specialized technical expertise. Additionally, concerns related to data privacy and ethical use of patient information must be addressed when developing AI-based healthcare systems.

Overall, the comparative analysis indicates that blockchain technology and artificial intelligence models complement each other in developing smart pharmaceutical supply chain systems. Blockchain provides secure and transparent data management, while AI-driven recommendation systems enable intelligent decision-making and personalized healthcare services. The integration of these technologies has the potential to transform the pharmaceutical industry by improving drug traceability, reducing counterfeit medications, and enhancing patient treatment outcomes.

Discussion

The integration of blockchain technology and artificial intelligence models in pharmaceutical supply chain management represents a significant advancement in addressing long-standing challenges related to transparency, drug authenticity, and efficient data management. The pharmaceutical supply chain is inherently complex, involving multiple stakeholders such as manufacturers, distributors, healthcare providers, pharmacies, and regulatory authorities. Ensuring reliable communication and data exchange among these stakeholders is essential for maintaining drug safety and preventing counterfeit products from entering the market. The literature reviewed in this study indicates that blockchain technology provides an effective solution for enhancing transparency and traceability across pharmaceutical supply chains.

Blockchain technology offers several advantages compared with traditional centralized database systems. One of the most important benefits is its decentralized architecture, which eliminates the need for a single controlling authority. In blockchain networks, every transaction is recorded across multiple nodes and verified through consensus mechanisms. This ensures that once a transaction is recorded, it cannot be altered or deleted without the agreement of the entire network. Such immutability is particularly valuable in pharmaceutical supply chains where maintaining accurate records of drug production, transportation, and storage is critical for ensuring patient safety.

Another key advantage of blockchain systems is their ability to enable end-to-end traceability of pharmaceutical products. Each stage of the drug distribution process—from manufacturing and packaging to transportation and retail delivery—can be recorded on the blockchain. This allows regulatory agencies and supply chain participants to verify the authenticity of pharmaceutical products in real time. By enabling stakeholders to track products throughout the supply chain, blockchain systems help reduce the risk of counterfeit medications entering the market.

In addition to improving supply chain transparency, blockchain technology also facilitates secure data sharing among stakeholders. Pharmaceutical supply chains

often involve sensitive data related to manufacturing processes, patient prescriptions, and regulatory compliance. Blockchain systems use cryptographic techniques to ensure that sensitive data remains secure while still allowing authorized participants to access relevant information. This capability improves collaboration among supply chain participants and enhances overall system efficiency.

Artificial intelligence plays a complementary role in enhancing pharmaceutical supply chain systems by enabling intelligent data analysis and decision-making. AI-based models can analyze large datasets generated by pharmaceutical supply chains, including production records, transportation data, and patient feedback. Machine learning algorithms can identify patterns within these datasets and generate predictive insights that support decision-making processes. For example, AI models can predict drug demand patterns, identify potential supply chain disruptions, and recommend optimal distribution strategies.

Drug recommendation systems represent another important application of artificial intelligence in the pharmaceutical industry. These systems analyze patient data such as medical history, symptoms, and treatment outcomes to recommend appropriate medications. Traditional recommendation systems often rely on collaborative filtering techniques that compare user preferences to generate recommendations. However, these methods may not fully capture the complex relationships between drugs, diseases, and patient characteristics.

Recent advances in deep learning have enabled the development of attention-based recommendation systems that improve prediction accuracy by focusing on the most relevant features within datasets. Contextual attention networks analyze multiple variables simultaneously, including patient demographics, environmental factors, and drug interactions. By assigning different weights to these variables, attention-based models can generate more accurate and personalized medication recommendations.

The Contextual White Shark Attention Network represents a novel approach that combines attention mechanisms with optimization algorithms to improve predictive performance. The White Shark Optimization algorithm is inspired by the hunting behavior of sharks and is used to optimize neural network parameters. By integrating this optimization algorithm with attention-based neural networks, researchers can enhance model performance and reduce prediction errors.

When combined with blockchain technology, AI-based recommendation systems create powerful frameworks for smart pharmaceutical supply chain management. Blockchain ensures that drug distribution data is securely recorded and verified, while AI models analyze this data to generate insights and recommendations. For example, blockchain systems can store verified information about drug manufacturing and distribution, which AI models can analyze to detect supply chain anomalies or predict future demand patterns.

Despite the numerous advantages of integrating blockchain and artificial intelligence technologies, several challenges remain. One of the primary challenges is the scalability of blockchain networks. As the number of transactions increases, maintaining high performance and low latency becomes more difficult. Researchers are currently exploring techniques such as off-chain processing and sharding to address scalability issues in blockchain systems.

Another challenge relates to data privacy and regulatory compliance. Pharmaceutical supply chains involve sensitive patient data that must be protected according to strict privacy regulations. Ensuring that blockchain-based systems comply with healthcare privacy standards such as HIPAA and GDPR remains an important research area.

Implementation cost is another barrier to the adoption of blockchain and AI technologies in pharmaceutical supply chains. Developing and maintaining distributed ledger systems requires significant investment in infrastructure and technical expertise. Small and medium-sized pharmaceutical companies may face challenges in adopting these technologies due to financial and resource constraints.

Furthermore, interoperability between blockchain platforms and existing healthcare information systems remains a technical challenge. Many healthcare organizations currently use legacy systems that may not be compatible with blockchain-based infrastructures. Developing standardized protocols and integration frameworks will be essential for enabling seamless data exchange between different systems.

Overall, the discussion highlights the transformative potential of blockchain and artificial intelligence technologies in building intelligent pharmaceutical supply chain systems. The integration of secure data management provided by blockchain with advanced predictive capabilities offered by AI models can significantly improve supply chain transparency, reduce counterfeit drugs, and enhance patient outcomes. Continued research in this area is expected to

lead to the development of more efficient and scalable smart pharmaceutical ecosystems.

Conclusion

The pharmaceutical supply chain is a critical component of global healthcare systems, responsible for ensuring the safe production, distribution, and delivery of medications to patients. However, traditional pharmaceutical supply chains face numerous challenges, including lack of transparency, limited traceability, counterfeit drug infiltration, and inefficient data sharing among stakeholders. These challenges highlight the need for innovative technological solutions that can improve supply chain security, transparency, and operational efficiency.

This systematic review examined recent research developments related to blockchain technology and artificial intelligence techniques for pharmaceutical supply chain management and drug recommendation systems. The analysis focused on studies published between 2020 and 2024 that explore the integration of distributed ledger technology with advanced machine learning models. The findings indicate that blockchain technology provides significant advantages in improving transparency, traceability, and data integrity within pharmaceutical supply chains. By recording transactions in a decentralized and immutable ledger, blockchain systems enable stakeholders to track pharmaceutical products throughout the entire supply chain lifecycle.

In addition to improving supply chain transparency, blockchain technology facilitates secure data sharing among stakeholders while maintaining data integrity and preventing unauthorized modifications. Smart contracts further enhance supply chain automation by enabling predefined transaction conditions to be executed automatically. These features contribute to more efficient supply chain operations and improved regulatory compliance.

Artificial intelligence techniques complement blockchain systems by enabling intelligent data analysis and predictive decision-making. AI-based recommendation systems can analyze large datasets related to patient health records, drug interactions, and clinical outcomes to generate personalized medication recommendations. Attention-based neural networks, in particular, have demonstrated strong capabilities in identifying relevant features within complex datasets and improving recommendation accuracy.

The integration of contextual attention networks with optimization algorithms such as White Shark Optimization further enhances the performance of AI-based recommendation systems. Optimization algorithms improve model training by identifying optimal parameter configurations, thereby increasing prediction accuracy and reducing computational costs.

One of the most promising developments identified in this review is the integration of blockchain technology with AI-driven recommendation systems to create intelligent pharmaceutical supply chain platforms. Such systems combine secure data management with advanced predictive analytics to provide both supply chain transparency and personalized healthcare recommendations. This integrated approach can significantly reduce the risk of counterfeit drugs, improve drug distribution efficiency, and enhance patient treatment outcomes.

Despite these promising developments, several challenges remain in implementing blockchain and AI technologies in real-world pharmaceutical supply chains. Scalability issues, high implementation costs, and interoperability challenges continue to limit the widespread adoption of these technologies. Additionally, ensuring compliance with healthcare data privacy regulations remains a critical concern.

Future research should focus on developing scalable blockchain architectures capable of handling large transaction volumes while maintaining high performance. Researchers should also explore advanced AI models that can analyze multimodal healthcare datasets including clinical records, genetic data, and patient feedback. Furthermore, developing standardized frameworks for integrating blockchain systems with existing healthcare infrastructures will be essential for enabling widespread adoption.

In conclusion, the integration of blockchain technology with advanced artificial intelligence models represents a transformative approach for modernizing pharmaceutical supply chains. These technologies have the potential to create secure, transparent, and intelligent pharmaceutical ecosystems that improve drug traceability, enhance supply chain efficiency, and support personalized healthcare services. Continued research and collaboration among industry stakeholders will be essential for realizing the full potential of these technologies in the smart pharmaceutical industry.

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