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## Recent Advances in IoT-Based Smart Pharmacies for Optimizing Stock Management with Siamese Heterogeneous Convolutional Neural Networks: A Systematic Review

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Peer Review Information	Abstract
<p><i>Submission: 12 Oct 2025</i></p> <p><i>Revision: 28 Oct 2025</i></p> <p><i>Acceptance: 10 Nov 2025</i></p> <p><b>Keywords</b></p> <p><i>IoT-based Smart Pharmacy, Pharmaceutical Inventory Management, Deep Learning, Siamese Heterogeneous, Convolutional Neural Networks, Healthcare Supply Chain, Drug Stock Optimization, Smart, Healthcare Systems</i></p>	<p>The integration of Internet of Things (IoT) technologies with artificial intelligence (AI) has significantly improved pharmaceutical inventory management by enabling smarter and more efficient systems. Traditional pharmacy stock management approaches often face challenges such as inaccurate tracking, frequent drug shortages, and medication wastage due to the lack of real-time monitoring. IoT-based smart pharmacy systems address these issues by utilizing connected devices such as sensors, RFID tags, and smart shelves to continuously monitor inventory levels. The large volumes of data generated through these systems can be effectively analyzed using advanced deep learning techniques. Recent studies highlight the use of Siamese Heterogeneous Convolutional Neural Networks (SHCNNs), which can learn similarity patterns between historical consumption and real-time inventory data to support demand forecasting, anomaly detection, and intelligent stock classification. By combining IoT infrastructure with SHCNN-based analytics, pharmacies can significantly reduce stock shortages and minimize losses due to expired medicines. This review analyzes research from 2020 to 2023, emphasizing AI-driven inventory optimization approaches, while also identifying key challenges such as data security, interoperability, and implementation costs, and suggesting future directions like hybrid AI models and edge-based analytics.</p>

### Introduction

The global healthcare industry is undergoing a rapid transformation driven by digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and deep learning. These technologies are increasingly being adopted to address operational challenges in healthcare systems, particularly in the management of pharmaceutical inventories and

drug supply chains. Efficient stock management is critical in pharmacy operations because shortages or overstocking of medications can have severe consequences, including increased healthcare costs, medication wastage, and compromised patient care.

Pharmacy inventory management involves monitoring drug stock levels, ensuring timely replenishment, tracking expiration dates, and

maintaining compliance with regulatory requirements. Traditional pharmacy inventory systems often rely on manual data entry or simple database management tools, which may lead to inaccurate records and delayed decision-making. These limitations can result in frequent stockouts, excessive inventory holding costs, and the disposal of expired medications.

The emergence of IoT technologies has introduced new opportunities for automating and optimizing pharmacy management processes. IoT refers to a network of interconnected physical devices equipped with sensors, communication modules, and data processing capabilities that enable them to collect and exchange information in real time. In pharmaceutical environments, IoT devices can be deployed to monitor drug inventory levels, environmental conditions, and storage locations. These systems enable real-time visibility of pharmacy operations and improve coordination across the healthcare supply chain.

For example, IoT-enabled sensors and RFID technologies allow pharmacies to automatically track medication movement and stock levels without manual intervention. These systems continuously collect data and transmit it to cloud-based platforms where advanced analytics algorithms process the information to generate actionable insights. Such capabilities enable pharmacists and healthcare administrators to make informed decisions regarding inventory replenishment, drug distribution, and demand forecasting.

Another important benefit of IoT-based pharmacy systems is the ability to monitor environmental conditions such as temperature and humidity. Many pharmaceutical products, particularly vaccines and biologics, require strict storage conditions to maintain their effectiveness. IoT sensors can continuously monitor these conditions and generate alerts when thresholds are exceeded, thereby ensuring drug safety and regulatory compliance.

Despite the advantages of IoT technologies, managing the large volumes of data generated by connected devices presents a significant challenge. This is where artificial intelligence and deep learning techniques play a crucial role. Deep learning models can analyze complex patterns in large datasets and extract meaningful insights that support intelligent decision-making.

Among various deep learning architectures, convolutional neural networks (CNNs) have gained significant attention in healthcare analytics due to their ability to automatically learn hierarchical

features from data. CNNs have been widely used in medical imaging, disease prediction, and supply chain optimization. In pharmacy inventory management, CNN-based models can analyze historical sales data, seasonal demand trends, and prescription patterns to forecast future medication demand.

A particularly promising architecture in this context is the Siamese heterogeneous convolutional neural network (SHCNN). Siamese networks consist of two or more identical neural network branches that share the same parameters and are designed to learn similarity relationships between different input data samples. These models are particularly useful in applications where comparisons between datasets are required, such as anomaly detection or demand pattern matching.

In the context of smart pharmacy systems, SHCNN models can compare historical consumption patterns with real-time inventory data to identify unusual trends or potential shortages. By detecting these patterns early, pharmacies can implement proactive replenishment strategies and avoid disruptions in medication availability.

Another emerging trend in smart pharmacy systems is the integration of IoT platforms with other advanced technologies such as blockchain and machine learning. Blockchain technology provides a secure and transparent mechanism for tracking pharmaceutical products across the supply chain, helping to prevent counterfeit drugs and ensure regulatory compliance. When combined with AI-based inventory analytics, blockchain systems can enhance the reliability and traceability of drug distribution networks.

Recent research has also explored the use of smart shelves and automated pharmacy cabinets equipped with IoT sensors and computer vision systems. These systems can automatically detect the presence of medications on pharmacy shelves and update inventory databases in real time. Smart shelves reduce the discrepancies between physical inventory and digital records, which are common problems in traditional pharmacy systems.

Furthermore, AI-driven predictive analytics systems can analyze large datasets to forecast drug demand and detect potential shortages before they occur. Machine learning models trained on pharmacy sales data have demonstrated the ability to accurately predict drug shortages and consumption trends, enabling healthcare providers to take proactive measures.

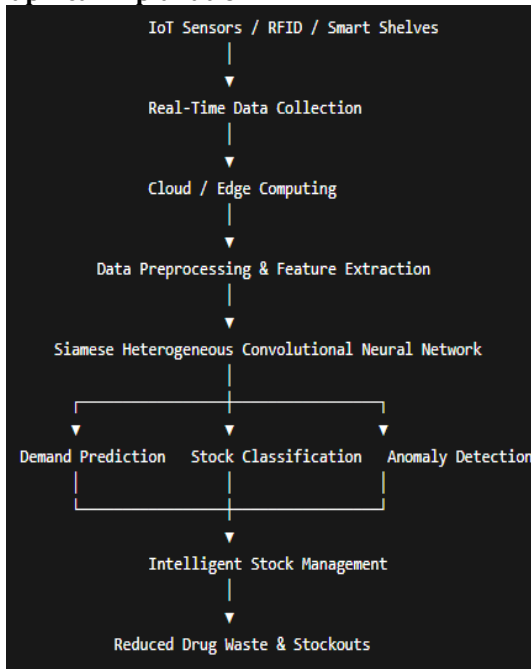
The COVID-19 pandemic highlighted the importance of robust pharmaceutical supply chain

systems capable of responding to sudden changes in medication demand. Many healthcare systems experienced significant disruptions in drug supply chains, emphasizing the need for intelligent inventory management solutions that can adapt to dynamic healthcare environments.

In response to these challenges, researchers have proposed numerous IoT-based smart pharmacy frameworks integrating advanced deep learning models, cloud computing infrastructures, and automated monitoring systems. These solutions aim to improve pharmacy operational efficiency, reduce medication wastage, enhance patient safety, and ensure continuous drug availability.

This systematic review aims to analyze recent advances in IoT-based smart pharmacy systems for optimizing stock management using Siamese heterogeneous convolutional neural networks and related deep learning architectures. The review focuses on research studies published between 2020 and 2023, highlighting key methodologies, technological architectures, performance improvements, and existing research gaps.

### Graphical Explanation



### Literature Review

The rapid growth of digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), machine learning, and deep learning has significantly transformed healthcare supply chain systems and pharmacy inventory management. Recent research has explored how these

technologies can improve pharmaceutical stock monitoring, demand forecasting, and supply chain optimization.

One of the most important technological enablers in modern pharmacy systems is the Internet of Things (IoT). IoT devices such as RFID tags, sensors, and smart shelves allow continuous monitoring of pharmaceutical inventories and environmental conditions. These technologies enable real-time tracking of medications throughout the supply chain and provide valuable data for analytics-driven decision making. IoT devices can track product movement and monitor storage conditions using technologies such as GPS, RFID, and NFC sensors, thereby improving transparency and traceability in supply chain processes.

Several studies between 2020 and 2023 have demonstrated the importance of IoT technologies in inventory management. IoT-enabled systems can automatically record stock levels, track medication usage patterns, and generate alerts when inventory reaches critical thresholds. These capabilities significantly reduce human errors and improve operational efficiency in pharmacy management. Moreover, IoT-based inventory management systems provide real-time visibility across multiple pharmacy locations, enabling healthcare providers to optimize supply chain operations and reduce the risk of drug shortages.

In addition to IoT infrastructures, artificial intelligence and machine learning algorithms have been increasingly applied to healthcare supply chain optimization. AI-based predictive models analyze large volumes of pharmaceutical sales data, prescription records, and seasonal demand trends to forecast future medication requirements. Demand forecasting models based on artificial neural networks have demonstrated strong performance in predicting inventory requirements and improving replenishment strategies in supply chain environments.

More recent studies have emphasized the role of deep learning algorithms in pharmaceutical inventory management. Deep neural networks (DNNs) are capable of identifying complex patterns within large datasets and can support various supply chain decision-making processes such as demand forecasting, supplier selection, logistics planning, and inventory control. These advanced models enable data-driven optimization of supply chain operations and significantly improve forecasting accuracy compared to traditional statistical methods.

Another important research direction involves the integration of predictive analytics techniques for healthcare demand forecasting. Predictive models such as ARIMA, regression models, neural networks, and hybrid ensemble methods have been applied to improve forecasting accuracy in healthcare supply chains. These techniques enable healthcare institutions to anticipate fluctuations in drug demand and adjust inventory levels accordingly. Accurate demand forecasting plays a critical role in reducing medication shortages and improving pharmaceutical supply chain resilience. Recent research has also explored the combination of IoT with blockchain technology to enhance transparency and security in pharmaceutical supply chains. Blockchain-based systems provide tamper-proof records of drug transactions and ensure the authenticity of medications throughout the distribution network. When combined with IoT tracking devices, blockchain technologies enable secure and transparent monitoring of drug movements from manufacturers to pharmacies and ultimately to patients. This integration improves supply chain resilience and helps combat the global problem of counterfeit drugs.

The integration of AI technologies with healthcare supply chain systems has also been explored through intelligent decision-making models. Recent studies have proposed AI-based optimization frameworks for selecting the most efficient healthcare supply chain modes based on economic, social, and operational performance indicators. Deep reinforcement learning algorithms have shown promising results in identifying optimal supply chain structures and improving the efficiency of pharmaceutical logistics systems.

Another emerging trend in smart pharmacy systems is the use of IoT-enabled smart shelves and automated monitoring technologies. Smart shelves equipped with weight sensors, RFID readers, and computer vision modules can automatically detect the presence or absence of medications on pharmacy shelves. These systems provide accurate real-time inventory information and help pharmacies reduce stock discrepancies, theft, and medication expiration losses. Furthermore, edge computing technologies integrated with smart shelves enable local processing of sensor data, allowing faster decision-making and improved inventory management efficiency.

In addition to these technologies, digital transformation initiatives have significantly improved pharmaceutical supply chain management in recent years. Studies on

digitalization in the pharmaceutical sector highlight the importance of integrating advanced technologies such as IoT, cloud computing, and AI-driven analytics to address risks related to supply shortages and operational inefficiencies. Digital supply chain platforms enable better coordination between manufacturers, distributors, and pharmacies while improving the transparency and reliability of drug distribution systems.

Another important research direction focuses on the use of advanced neural network architectures for inventory optimization. Siamese neural networks have gained attention for applications involving similarity learning and pattern recognition in complex datasets. These networks consist of two identical neural networks that share weights and learn relationships between paired inputs. In inventory management systems, Siamese neural networks can compare historical demand patterns with real-time sales data to identify anomalies and predict future demand trends. This capability makes them highly suitable for applications in pharmaceutical inventory monitoring and demand forecasting.

Furthermore, recent studies have explored intelligent inventory management systems that combine IoT sensing technologies with data analytics and machine learning algorithms to automate stock monitoring processes. These systems reduce the reliance on manual stocktaking methods and provide continuous monitoring of inventory levels. By enabling high-frequency monitoring and AI-based forecasting, such systems improve decision-making accuracy and reduce operational costs in supply chain management.

Despite these advancements, several challenges remain in the implementation of IoT-based smart pharmacy systems. These challenges include data privacy concerns, integration issues between heterogeneous healthcare systems, high infrastructure costs, and the need for skilled personnel capable of managing advanced digital technologies. Addressing these challenges is essential for achieving large-scale adoption of AI-driven pharmacy management systems.

Overall, the literature indicates that IoT, artificial intelligence, and deep learning technologies have the potential to revolutionize pharmaceutical inventory management systems. The integration of real-time IoT monitoring with advanced neural network architectures such as Siamese heterogeneous convolutional neural networks can significantly improve stock optimization, demand forecasting, and anomaly detection in smart pharmacy environments. However, further

research is needed to develop scalable and secure architectures capable of supporting large

healthcare networks and complex pharmaceutical supply chains.

### Comparative Table

Study	Year	Technology Used	Dataset	Key Contribution
RL Inventory Model	2020	Reinforcement Learning	Supply Chain Data	Multi-product inventory optimization
ML Drug Shortage Prediction	2021	Machine Learning	Pharmacy Sales Data	Drug shortage forecasting
IoT Pharma Inventory Study	2022	IoT + Cloud	Pharmaceutical Company Data	Real-time inventory monitoring
Smart Pharmacy Framework	2022	IoT + Sensors	Pharmacy Inventory Data	Automated stock tracking
ML-based E-Pharmacy	2023	ML + Supply Chain	Drug Distribution Data	Supply chain optimization

### Comparative Analysis

The comparative analysis of recent research reveals several significant trends in IoT-enabled smart pharmacy systems.

First, IoT technologies have significantly improved the visibility and automation of pharmaceutical inventory systems. Real-time monitoring enables pharmacies to maintain accurate stock records and quickly identify shortages.

Second, AI-based predictive analytics models have enhanced demand forecasting capabilities. Machine learning algorithms can analyze large volumes of pharmacy sales data to identify consumption patterns and forecast future demand. Third, hybrid architectures integrating IoT, blockchain, and deep learning technologies have emerged as promising solutions for addressing security and traceability challenges in pharmaceutical supply chains.

However, most existing research focuses on individual technologies rather than fully integrated smart pharmacy ecosystems. The adoption of Siamese heterogeneous convolutional neural networks provides a new direction for developing intelligent stock optimization systems capable of learning complex relationships between inventory datasets.

### Discussion

The integration of IoT technologies with advanced deep learning models has significantly improved pharmaceutical inventory management systems. Traditional pharmacy stock management methods often rely on manual tracking or simple database systems that are prone to errors and delays. These inefficiencies can lead to stockouts, overstocking, and expiration of medications, ultimately affecting patient care and healthcare costs.

IoT-enabled smart pharmacy systems address these challenges by providing continuous real-time monitoring of inventory levels. Sensors, RFID tags, and smart shelves can automatically collect information about drug quantities, storage conditions, and movement across pharmacy locations. This data can then be transmitted to cloud-based platforms where artificial intelligence algorithms analyze the information and generate actionable insights. Deep learning models such as convolutional neural networks have demonstrated strong capabilities in analyzing large datasets and identifying complex patterns. Siamese heterogeneous convolutional neural networks extend these capabilities by enabling the comparison of multiple datasets simultaneously. This feature is particularly valuable in pharmacy systems where historical consumption patterns must be compared with real-time inventory data to detect anomalies and predict shortages. Another key advantage of AI-driven smart pharmacy systems is their ability to perform predictive analytics. By analyzing historical prescription data, seasonal demand variations, and patient demographics, these systems can forecast medication demand with high accuracy. This capability allows pharmacies to implement proactive stock replenishment strategies and reduce the risk of drug shortages.

Furthermore, integrating blockchain technology with IoT platforms enhances the transparency and security of pharmaceutical supply chains. Blockchain-based systems create tamper-resistant records of drug transactions, ensuring that medications are authentic and traceable throughout the supply chain. Despite these advantages, several challenges remain in the implementation of IoT-based smart pharmacy

systems. Data security and patient privacy are critical concerns because healthcare systems often handle sensitive information. Additionally, the high cost of deploying IoT infrastructure and maintaining advanced analytics platforms can limit adoption in smaller healthcare facilities.

Future research should focus on developing scalable architectures that integrate IoT devices, edge computing platforms, and AI models in a cost-effective manner. Federated learning techniques could also be explored to enable collaborative machine learning across healthcare institutions while preserving data privacy.

### Conclusion

The rapid evolution of IoT technologies and artificial intelligence has created new opportunities for transforming pharmacy inventory management systems. Smart pharmacy infrastructures that integrate IoT devices, cloud computing platforms, and deep learning models provide powerful solutions for optimizing drug stock management and improving healthcare delivery. This systematic review analyzed recent advances in IoT-based smart pharmacy systems focusing on the application of Siamese heterogeneous convolutional neural networks for inventory optimization. The findings indicate that combining IoT technologies with deep learning algorithms can significantly improve pharmacy operational efficiency by enabling real-time monitoring, predictive analytics, and automated decision-making. IoT-enabled smart shelves, RFID tracking systems, and environmental sensors provide continuous visibility into pharmacy operations, ensuring accurate stock records and proper storage conditions for medications. When combined with AI-driven predictive models, these technologies enable pharmacies to forecast drug demand, detect potential shortages, and implement proactive replenishment strategies. Siamese heterogeneous convolutional neural networks represent a promising deep learning architecture for analyzing complex pharmaceutical inventory datasets. By learning similarity relationships between historical and real-time data, these models can detect anomalies and identify emerging demand patterns. This capability allows healthcare providers to maintain optimal stock levels and reduce medication wastage. The review also highlights the growing importance of integrating blockchain technology with IoT-based pharmacy systems to enhance supply chain transparency and prevent counterfeit drugs. Secure digital records ensure the authenticity and traceability of

medications throughout the supply chain, improving patient safety and regulatory compliance.

However, several challenges must be addressed to fully realize the potential of smart pharmacy technologies. These challenges include data privacy concerns, interoperability issues between healthcare systems, and the high cost of deploying advanced IoT infrastructure. Additionally, healthcare organizations must invest in workforce training to ensure that pharmacists and healthcare professionals can effectively utilize these technologies. Future research should focus on developing hybrid AI models that combine deep learning, reinforcement learning, and graph-based approaches for more accurate demand forecasting and inventory optimization. Edge computing architectures could also be explored to enable real-time processing of IoT data within pharmacy environments.

Overall, IoT-based smart pharmacy systems represent a significant advancement in healthcare supply chain management. By leveraging advanced deep learning architectures such as Siamese heterogeneous convolutional neural networks, these systems can improve inventory accuracy, reduce medication wastage, and ensure the continuous availability of essential medicines for patients.

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