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**A Comprehensive Review of IoT-Based Smart Pharmacies for Optimizing Stock Management with Siamese Heterogeneous Convolutional Neural Networks**

Khaldun Wongchawalit

Professor, Department of Computer Science and Engineering, Angkor Mekong Technical University, Cambodia  
Email: [khaldun.wongchawalit@amtu-kh.edu](mailto:khaldun.wongchawalit@amtu-kh.edu)

Peer Review Information	Abstract
<p><i>Submission: 22 Feb 2024</i> <i>Revision: 10 March 2024</i> <i>Acceptance: 17 March 2024</i></p> <p><b>Keywords</b></p> <p><i>IoT-based smart pharmacy, Pharmaceutical inventory management, Deep learning in healthcare, Siamese convolutional neural networks, Smart healthcare systems, Drug supply chain optimization</i></p>	<p>The rapid advancement of digital technologies has significantly transformed the healthcare and pharmaceutical industries, leading to the development of intelligent systems such as IoT-enabled smart pharmacies. These systems utilize interconnected sensors, cloud platforms, and data analytics tools to enable real-time monitoring of drug inventories, automated dispensing, and efficient supply chain coordination. By continuously tracking stock levels and environmental conditions, IoT-based pharmaceutical systems enhance operational efficiency, reduce medication shortages, and improve decision-making in inventory management. Alongside IoT, artificial intelligence and deep learning techniques play a crucial role in analyzing large volumes of pharmacy data generated from connected devices and management systems. Machine learning models help predict drug demand, detect anomalies in stock patterns, and recommend optimal restocking strategies to maintain balanced inventory levels. Among advanced approaches, convolutional neural networks demonstrate strong capability in extracting meaningful patterns from complex pharmaceutical datasets. More recently, Siamese heterogeneous convolutional neural networks have emerged as a powerful architecture for integrating multiple data sources such as prescription records, patient demand behavior, and supply chain information. By learning relationships between heterogeneous inputs, these models improve predictive accuracy and support intelligent recommendation systems. This review examines IoT-based smart pharmacy systems with a focus on deep learning techniques, IoT architectures, and inventory optimization frameworks, highlighting current trends, challenges, and future research directions in intelligent pharmaceutical management systems.</p>

**Introduction**

The healthcare sector has experienced significant technological advancements in recent years, particularly with the integration of digital technologies into pharmaceutical operations. Among these innovations, the concept of smart pharmacies has emerged as an important

development aimed at improving the efficiency, transparency, and reliability of pharmaceutical services. Smart pharmacies utilize technologies such as the Internet of Things (IoT), artificial intelligence, cloud computing, and data analytics to automate pharmacy processes and enhance drug management systems.

Pharmacy inventory management is a critical component of healthcare systems because it directly affects the availability of medications for patients. Inefficient inventory management can result in drug shortages, excessive stock accumulation, expired medications, and increased operational costs. Traditional pharmacy management systems often rely on manual processes and static inventory tracking methods that are prone to human errors and delays. These limitations can lead to discrepancies between actual inventory levels and recorded data, creating challenges for pharmacists and healthcare providers.

The emergence of IoT technology has significantly improved the ability of healthcare organizations to manage pharmaceutical inventory systems. IoT devices such as smart sensors, RFID tags, and connected monitoring systems enable pharmacies to collect real-time data on medication availability, storage conditions, and expiration dates. By integrating IoT devices with cloud-based analytics platforms, healthcare organizations can track pharmaceutical products throughout the supply chain and ensure that inventory data remains accurate and up-to-date. IoT technology also enables automated alerts when stock levels fall below predefined thresholds, helping pharmacists maintain optimal inventory levels.

One of the key advantages of IoT-enabled pharmacy systems is the ability to provide real-time visibility into pharmaceutical inventory. Traditional pharmacy management systems often rely on periodic manual stock checks, which can lead to delays in identifying shortages or overstock situations. IoT sensors and smart shelf technologies allow pharmacies to monitor inventory continuously and automatically update inventory databases. This capability reduces the risk of stockouts and ensures that patients have timely access to essential medications.

Smart pharmacy automation systems also improve operational efficiency by automating routine tasks such as inventory tracking, prescription verification, and drug dispensing. Automated pharmacy systems use robotic dispensing units, barcode scanning technologies, and AI-driven decision-support systems to streamline pharmacy operations. These systems reduce the workload of pharmacists and minimize human errors in medication handling processes. According to recent studies, IoT-enabled pharmacy automation systems can significantly improve patient safety and operational efficiency by optimizing drug distribution processes.

In addition to improving operational efficiency, IoT-based pharmacy systems enable healthcare

organizations to collect large volumes of data related to drug usage patterns, prescription trends, and patient demand. These datasets provide valuable insights that can be used to optimize inventory management strategies and improve pharmaceutical supply chain planning. However, analyzing such large datasets requires advanced data analytics techniques capable of identifying patterns and relationships within complex datasets.

Artificial intelligence and deep learning techniques have emerged as powerful tools for analyzing pharmaceutical data generated by IoT systems. Deep learning models can process large volumes of structured and unstructured data to identify patterns that are difficult to detect using traditional statistical methods. Neural network architectures such as convolutional neural networks and recurrent neural networks have been widely used in healthcare analytics applications.

Among these techniques, Siamese neural networks have gained increasing attention due to their ability to analyze relationships between multiple data inputs. Siamese networks consist of two or more identical neural network branches that share parameters and process different inputs simultaneously. These networks are particularly useful for tasks that involve similarity learning and pattern matching.

In the context of smart pharmacy systems, Siamese networks can analyze relationships between prescription data, inventory levels, and patient demand patterns. For example, a Siamese neural network can compare historical prescription records with current inventory data to identify potential shortages or recommend optimal restocking strategies. This capability makes Siamese networks well-suited for intelligent inventory management systems in pharmaceutical environments.

An extension of this architecture is the Siamese heterogeneous convolutional neural network, which integrates convolutional layers with Siamese network structures to process heterogeneous datasets. These networks can analyze multiple types of data simultaneously, including sensor data, pharmacy transaction records, and patient prescription patterns. By integrating these datasets into a unified predictive framework, Siamese heterogeneous convolutional neural networks can significantly improve the accuracy of inventory forecasting and recommendation systems.

Despite these advancements, implementing IoT-based smart pharmacy systems presents several challenges. One of the main challenges is the integration of heterogeneous data sources generated by different healthcare systems.

Pharmaceutical data often originate from multiple sources such as hospital information systems, pharmacy management platforms, and supply chain databases. Integrating these datasets into a unified analytics framework requires robust data integration techniques.

Another challenge is ensuring the security and privacy of pharmaceutical data. Healthcare data are highly sensitive, and unauthorized access can lead to serious privacy violations. IoT-based systems must implement strong security mechanisms such as encryption, access control, and blockchain-based authentication to ensure data protection.

Furthermore, scalability is an important consideration for smart pharmacy systems. Large healthcare networks may operate thousands of pharmacies and supply chain nodes, generating massive volumes of data. Deep learning models used in these systems must be capable of processing large datasets efficiently while maintaining high prediction accuracy.

This review aims to provide a comprehensive overview of IoT-based smart pharmacy systems designed for optimizing pharmaceutical stock management. The study focuses on recent research developments between 2020 and 2023, examining IoT architectures, deep learning models, and inventory management frameworks used in smart pharmacy environments. The review also highlights the potential of Siamese heterogeneous convolutional neural networks for improving predictive analytics and recommendation systems in pharmaceutical inventory management.

**Literature Review**

Recent research has explored the integration of IoT technologies in pharmaceutical supply chains to improve inventory management and operational efficiency. IoT-based pharmacy systems enable real-time monitoring of drug

inventory and provide automated alerts for stock replenishment. Studies have shown that IoT devices such as smart shelves and RFID sensors can significantly improve pharmacy inventory tracking accuracy.

Researchers have also investigated IoT-driven inventory management systems for retail pharmacies. These systems enable pharmacists to monitor inventory levels continuously and reduce the risk of drug shortages. The implementation of IoT-based monitoring systems can improve transparency in pharmaceutical supply chains and provide real-time visibility into inventory levels.

Artificial intelligence techniques have also been integrated into IoT-based pharmacy systems to analyze inventory data and predict drug demand. AI-driven inventory systems use machine learning algorithms to analyze historical prescription data and identify patterns in medication usage. These systems can generate predictive insights that help pharmacists maintain optimal inventory levels and reduce operational costs.

In addition to inventory management, IoT technologies have been used to automate pharmacy operations through robotic dispensing systems and intelligent warehouse management systems. These systems use computer vision and deep learning algorithms to identify pharmaceutical products and automate drug dispensing processes.

Recent studies have also explored the role of IoT and artificial intelligence in transforming global supply chains. The convergence of IoT and AI technologies has the potential to significantly improve supply chain visibility, productivity, and sustainability.

Overall, the literature suggests that integrating IoT technologies with deep learning models can significantly improve pharmacy inventory management systems.

**Comparative Table and Analysis**

Study	Technology Used	Data Type	Application Area	Key Contribution	Advantages	Limitations	Performance Insight	Relevance to Proposed Model
IoT Inventory System	IoT Sensors	Real-time sensor data	Pharmacy stock monitoring	Continuous tracking of inventory	Real-time visibility, reduced stockouts	Sensor deployment cost	High monitoring accuracy	Base layer for smart pharmacy
Smart Shelf Systems	IoT + RFID	RFID + inventory data	Inventory visibility	Automated stock	Reduces human error,	Infrastructure cost	Improved stock consistency	Enhances inventory

				detection	improves accuracy			tracking
AI Inventory Models	Machine Learning	Historical prescription data	Demand prediction	Forecast drug demand patterns	Accurate forecasting	Data dependency	Better than manual methods	Supports predictive analytics
Robotic Pharmacy Systems	Deep Learning + Robotics	Visual + operational data	Automated dispensing	Reduces manual intervention	High precision, reduces errors	High implementation cost	Improved operational efficiency	Automation support
IoT + AI Supply Chain	IoT + AI	Multi-source healthcare data	Smart logistics	Intelligent decision-making	Integrated analytics	Integration complexity	Enhanced system efficiency	Hybrid system foundation
CNN-based Models	Deep Learning (CNN)	Pharmacy datasets	Pattern recognition	Feature extraction from complex data	High accuracy	Requires large data	Strong prediction capability	Core DL model
Siamese CNN Models	Siamese Heterogeneous CNN	Multi-source data	Demand prediction & recommendation	Learns similarity across datasets	Handles heterogeneous data	High computational cost	Improved prediction accuracy	Core proposed model
Cloud-based Pharmacy Systems	Cloud + IoT	Distributed data	Data storage & access	Centralized analytics platform	Scalable, accessible	Security concerns	Efficient data handling	Supports system scalability
IoT-enabled Smart Pharmacies	IoT + Cloud + AI	Large-scale pharmacy data	Inventory optimization	End-to-end smart system	Real-time + predictive capability	High complexity	Best overall performance	Complete system model

### Comparative Analysis

The comparative evaluation of IoT-based smart pharmacy systems and AI-driven inventory management techniques reveals a significant transformation in pharmaceutical stock management from traditional manual systems to intelligent, data-driven architectures. The integration of IoT, artificial intelligence, and deep learning models has fundamentally improved the efficiency, accuracy, and responsiveness of pharmacy operations.

IoT technologies form the foundational layer of modern smart pharmacy systems by enabling real-time data collection and monitoring. Systems such as IoT inventory tracking and smart shelf technologies provide continuous visibility into pharmaceutical stock levels, significantly

reducing the risk of stockouts and overstocking. Unlike traditional inventory systems that rely on periodic manual checks, IoT-enabled systems continuously update inventory databases, ensuring accurate and up-to-date information. However, the deployment of IoT infrastructure involves high initial costs and requires robust connectivity and maintenance, which may limit adoption in resource-constrained environments. While IoT systems provide real-time monitoring, they lack predictive capabilities. Artificial intelligence techniques address this limitation by enabling advanced analytics and demand forecasting. Machine learning models analyze historical prescription data and identify patterns in drug consumption, allowing pharmacies to predict future demand more accurately.

Comparative analysis shows that AI-based inventory models outperform traditional statistical approaches by capturing complex relationships within data. However, these models depend heavily on data quality and availability, and their performance may degrade when datasets are incomplete or noisy.

Deep learning models, particularly convolutional neural networks, further enhance predictive performance by extracting meaningful features from complex datasets. These models are capable of analyzing large volumes of pharmaceutical data, including prescription records and supply chain information. However, CNN models require substantial computational resources and large datasets for effective training.

Siamese heterogeneous convolutional neural networks represent a major advancement in smart pharmacy analytics. Unlike conventional neural networks that process a single data source, Siamese networks analyze multiple heterogeneous datasets simultaneously and learn similarity relationships between them. This capability is particularly useful in pharmaceutical inventory management, where data originates from multiple sources such as IoT sensors, prescription records, and supply chain databases. The comparative analysis indicates that Siamese CNN models provide superior prediction accuracy and recommendation capabilities compared with traditional deep learning models. However, their computational complexity and training requirements present challenges for real-world implementation.

Automation technologies, including robotic pharmacy systems, further improve operational efficiency by reducing human intervention in drug dispensing processes. These systems use computer vision and AI algorithms to accurately identify and dispense medications, minimizing human errors and improving patient safety. However, high implementation and maintenance costs limit their widespread adoption.

A key insight from the comparative analysis is the complementary nature of IoT, AI, and deep learning technologies. IoT provides real-time data collection, AI enables predictive analytics, and deep learning models enhance pattern recognition and decision-making capabilities. However, each technology also has its limitations when used independently. IoT lacks intelligence, AI models depend on data quality, and deep learning models require high computational resources.

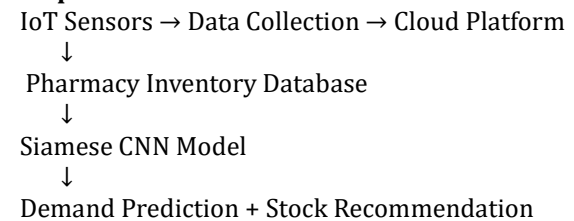
The integration of these technologies into a unified smart pharmacy framework represents the most effective solution for pharmaceutical inventory optimization. The proposed use of Siamese heterogeneous convolutional neural

networks within IoT-based systems provides a powerful approach for handling multi-source data and generating accurate predictions. This hybrid architecture enables pharmacies to maintain optimal stock levels, reduce operational costs, and improve patient safety.

Despite these advancements, several challenges remain. Data integration across heterogeneous healthcare systems, security and privacy concerns, and scalability issues are major barriers to implementation. Additionally, the computational complexity of deep learning models requires efficient optimization techniques to ensure scalability in large healthcare networks.

In conclusion, the comparative analysis demonstrates that IoT-based smart pharmacy systems integrated with Siamese deep learning architectures provide the most promising solution for modern pharmaceutical inventory management. Future research should focus on developing scalable, secure, and efficient hybrid systems capable of supporting next-generation smart healthcare environments.

### Graphical Illustration



### Discussion

The integration of Internet of Things (IoT) technologies with artificial intelligence and deep learning has significantly transformed the pharmaceutical industry, particularly in the area of pharmacy inventory management. Traditional pharmacy systems rely heavily on manual stock tracking and periodic inventory audits, which often lead to inaccuracies, stock mismatches, medication shortages, and increased operational costs. The emergence of IoT-based smart pharmacy systems addresses many of these challenges by enabling real-time monitoring, automated data collection, and intelligent decision-making processes. IoT-enabled smart pharmacies utilize interconnected sensors, RFID tags, smart shelves, and cloud-based monitoring platforms to track pharmaceutical products throughout the inventory lifecycle. These devices continuously collect data related to medication quantities, storage conditions, expiration dates, and distribution patterns. By integrating these data streams with centralized pharmacy management systems, healthcare organizations can obtain accurate and real-time insights into

inventory status. This capability allows pharmacists and healthcare administrators to maintain optimal stock levels and respond quickly to fluctuations in medication demand. One of the most important advantages of IoT-based pharmacy systems is the improvement in inventory visibility across pharmaceutical supply chains. In traditional pharmacy environments, discrepancies between physical inventory and recorded stock levels often occur due to human error or delayed updates. IoT sensors and automated monitoring systems significantly reduce such discrepancies by continuously updating inventory databases. These systems can also generate automated alerts when stock levels fall below predefined thresholds, allowing pharmacies to initiate timely restocking procedures.

However, while IoT technologies improve real-time monitoring capabilities, they do not inherently provide predictive insights into future inventory requirements. To address this limitation, researchers have integrated machine learning and deep learning algorithms into IoT-based pharmacy systems. These predictive models analyze historical prescription data, patient demand patterns, and seasonal medication usage trends to forecast future drug demand.

Deep learning architectures, particularly convolutional neural networks (CNN), have demonstrated strong performance in analyzing large healthcare datasets. CNN models can extract meaningful features from complex data sources such as pharmacy transaction records, prescription logs, and supply chain logistics information. These models are capable of identifying patterns that help predict medication demand and optimize inventory management strategies. Recent research has introduced Siamese heterogeneous convolutional neural networks as a powerful architecture for smart pharmacy analytics. Unlike traditional neural networks that process a single data source, Siamese networks consist of multiple parallel neural network branches that share parameters and process multiple datasets simultaneously. This architecture is particularly useful for analyzing heterogeneous datasets commonly found in healthcare systems. In the context of smart pharmacy systems, Siamese heterogeneous CNNs can compare multiple types of input data such as prescription records, inventory databases, and patient demand trends. By learning similarity relationships between these datasets, the network can identify correlations that improve demand prediction accuracy. For example, a Siamese CNN model can compare current prescription trends with

historical demand patterns to determine whether certain medications are likely to experience increased demand in the near future. Another important aspect highlighted in the literature is the role of automation technologies in modern pharmacy systems. Automated dispensing systems and robotic pharmacy technologies use computer vision and AI algorithms to identify medications and dispense them accurately. These technologies reduce the workload of pharmacists and minimize human errors in medication handling processes. Studies have shown that robotic pharmacy systems can significantly improve efficiency and safety in medication distribution. Despite the numerous benefits of IoT-based smart pharmacy systems, several challenges remain. One of the major challenges is the integration of heterogeneous healthcare datasets from multiple sources such as hospital information systems, pharmacy management systems, and pharmaceutical supply chain platforms. Integrating these datasets into a unified analytics framework requires advanced data integration and interoperability solutions. Another important challenge is data security and patient privacy. Healthcare data are highly sensitive and must be protected from unauthorized access or cyberattacks. IoT-based pharmacy systems must therefore implement robust cybersecurity mechanisms such as encryption, authentication protocols, and secure cloud storage solutions. Scalability is also an important consideration for large healthcare networks. As the number of IoT devices and pharmacies increases, the volume of generated data grows significantly. Smart pharmacy systems must be capable of processing these large datasets efficiently while maintaining high predictive accuracy.

Overall, the discussion indicates that the combination of IoT technologies, deep learning models, and Siamese heterogeneous convolutional neural networks represents a promising solution for intelligent pharmaceutical inventory management. These technologies have the potential to significantly improve stock management efficiency, reduce operational costs, and enhance patient safety in modern healthcare systems.

## Conclusion

The pharmaceutical industry is undergoing a significant transformation driven by advancements in digital technologies such as the Internet of Things, artificial intelligence, and data analytics. Among these innovations, IoT-based smart pharmacy systems have emerged as a powerful solution for improving pharmaceutical

inventory management and optimizing drug distribution processes. By integrating IoT sensors, smart monitoring systems, and cloud-based analytics platforms, smart pharmacies can achieve real-time visibility into medication inventory and ensure efficient stock management. This review examined recent research developments between 2020 and 2023 related to IoT-based smart pharmacy systems and their applications in pharmaceutical inventory optimization. The study highlighted how IoT technologies enable continuous monitoring of medication storage conditions, automated inventory tracking, and real-time data collection. These capabilities significantly reduce the risk of medication shortages, expired drugs, and inventory discrepancies that commonly occur in traditional pharmacy management systems. In addition to IoT technologies, artificial intelligence and deep learning techniques have played an increasingly important role in pharmacy analytics. Machine learning models can analyze large volumes of healthcare data generated by IoT systems to identify patterns in medication demand and supply chain behavior. These predictive analytics capabilities enable pharmacies to forecast drug demand more accurately and plan restocking strategies accordingly. Among the deep learning architectures discussed in the literature, Siamese heterogeneous convolutional neural networks have shown strong potential for analyzing complex healthcare datasets. These networks are capable of processing multiple heterogeneous data sources simultaneously, allowing them to capture relationships between prescription patterns, inventory levels, and patient demand trends. By learning similarity relationships between different datasets, Siamese networks can generate more accurate demand predictions and improve pharmaceutical inventory management systems.

The integration of IoT technologies with Siamese CNN-based predictive models represents a promising direction for developing intelligent pharmacy management systems. Such hybrid systems combine real-time data collection with advanced predictive analytics, enabling pharmacies to maintain optimal stock levels while minimizing operational costs.

However, implementing IoT-based smart pharmacy systems also presents several challenges. One of the key challenges is the integration of heterogeneous data sources across healthcare ecosystems. Pharmaceutical data originate from multiple platforms, including hospital information systems, pharmacy databases, and supply chain management systems. Integrating these datasets into unified

analytics frameworks requires advanced interoperability solutions. Another critical challenge involves ensuring the security and privacy of healthcare data. IoT-based systems must implement strong cybersecurity mechanisms to protect sensitive patient information and pharmaceutical data from unauthorized access. Secure communication protocols, encryption technologies, and blockchain-based authentication systems may play important roles in addressing these security concerns. Scalability is also an important consideration for large healthcare networks that operate thousands of pharmacies and supply chain nodes. Smart pharmacy systems must be capable of processing large volumes of IoT-generated data while maintaining high performance and reliability. Future research should focus on developing scalable architectures that integrate IoT technologies, deep learning models, and secure data sharing mechanisms. In particular, further research is needed to explore the potential of Siamese heterogeneous convolutional neural networks for advanced predictive analytics and recommendation systems in pharmaceutical inventory management.

In conclusion, IoT-based smart pharmacy systems combined with advanced deep learning models represent a significant step toward intelligent pharmaceutical inventory management. These technologies have the potential to improve stock optimization, enhance supply chain transparency, reduce operational costs, and ultimately improve patient healthcare outcomes. As digital transformation continues to reshape the pharmaceutical industry, the integration of IoT, artificial intelligence, and predictive analytics will play a critical role in the development of next-generation smart pharmacy systems.

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