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Artificial Intelligence Techniques for IoT-Based Smart Pharmacies for Optimizing Stock Management with Siamese Heterogeneous Convolutional Neural Networks: Trends and Challenges

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Abstract

The increasing demand for efficient pharmaceutical supply chain management has led to the adoption of Artificial Intelligence (AI) and Internet of Things (IoT) technologies in smart pharmacy systems. Traditional pharmacy inventory management often suffers from issues such as drug shortages, overstocking, and medication wastage due to limited forecasting capabilities and manual monitoring processes. AI-driven systems integrated with IoT sensors enable real-time monitoring of pharmaceutical inventory and predictive demand analysis, allowing pharmacies to maintain optimal stock levels. Recent advances in deep learning, particularly Siamese Heterogeneous Convolutional Neural Networks (SH-CNN), provide powerful tools for analyzing heterogeneous pharmacy data and identifying patterns in drug consumption trends. This review examines recent developments in recent years in AI-based IoT smart pharmacy systems for optimizing stock management. The study highlights key technologies, research trends, and challenges associated with implementing intelligent pharmacy systems. The findings suggest that integrating AI, IoT, and deep learning architectures can significantly improve inventory accuracy, reduce medication waste, and enhance pharmacy supply chain efficiency, while challenges related to data security, system integration, and scalability remain important areas for future research.

Introduction

Artificial intelligence and Internet of Things (IoT) technologies are transforming pharmaceutical inventory management by enabling smarter, faster, and more reliable pharmacy operations. Traditional inventory management methods often depend on manual record-keeping and delayed stock updates, resulting in medication shortages, overstocking, expired drugs, and operational inefficiencies. As pharmaceutical supply chains become increasingly complex, healthcare organizations are adopting AI, IoT, big data analytics, and cloud computing to automate inventory monitoring and improve decision-making. AI-based pharmacy management systems analyze prescription histories, patient demographics, disease trends, and seasonal demand to accurately forecast medication requirements, helping pharmacies maintain optimal stock levels while minimizing waste and ensuring continuous drug availability.

IoT technologies further strengthen pharmacy inventory systems through real-time monitoring of pharmaceutical products. Smart devices such as RFID tags, sensor-enabled storage units, and intelligent shelves continuously monitor inventory levels, storage conditions, and medication expiration dates. The collected data are transmitted to cloud platforms, where AI algorithms generate automated alerts for stock replenishment and inventory optimization. This real-time monitoring significantly improves inventory accuracy, reduces manual errors, and enhances the overall efficiency of pharmacy operations. By integrating IoT with cloud computing, healthcare organizations can achieve better visibility across pharmaceutical supply chains and respond rapidly to changing medication demands.

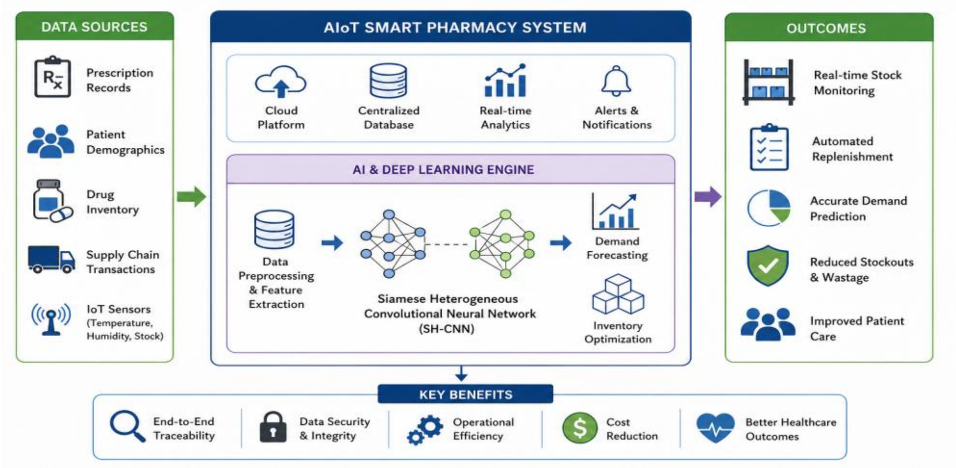


Figure 1. Smart Inventory Management Framework

Recent advances in deep learning have introduced powerful techniques for pharmaceutical inventory forecasting and management. Convolutional Neural Networks (CNNs) effectively extract patterns from heterogeneous healthcare datasets, while Siamese Heterogeneous Convolutional Neural Networks (SH-CNNs) enhance demand prediction by comparing similarities between historical prescription patterns, patient populations, and regional consumption trends. These intelligent models support automated inventory planning, demand forecasting, and supply chain optimization. The integration of AI, IoT, and Siamese deep learning architectures has led to the development of smart pharmacy ecosystems capable of autonomous inventory monitoring, predictive analytics, and intelligent decision support for pharmacists and healthcare administrators.

Despite these technological advancements, several challenges remain. Integrating heterogeneous healthcare data sources, ensuring interoperability among different healthcare platforms, maintaining patient privacy, and securing sensitive prescription information continue to be major concerns. Additionally, deploying IoT infrastructure and advanced AI systems requires substantial financial investment and technical expertise, limiting adoption in smaller healthcare facilities. Continuous model training, validation, and system monitoring are also necessary to maintain reliable forecasting performance and prevent medication shortages or excessive inventory.

This review examines recent developments in AI-driven IoT-enabled smart pharmacy systems, with particular emphasis on Siamese Heterogeneous Convolutional Neural Networks for pharmaceutical inventory optimization. It analyzes existing methodologies, identifies current technological trends and implementation challenges, and discusses future research directions aimed at developing scalable, secure, and intelligent pharmacy inventory management systems that improve operational efficiency, reduce medication waste, and enhance patient care.

Literature Review

The rapid development of Artificial Intelligence (AI), Internet of Things (IoT), and deep learning technologies has significantly transformed pharmaceutical supply chain management and pharmacy inventory systems. Researchers between 2020 and 2023 have explored various machine learning and IoT-based approaches for improving drug demand forecasting, reducing medication waste, and optimizing pharmaceutical inventory management. These studies highlight the increasing importance of intelligent pharmacy systems capable of autonomous decision-making and real-time monitoring.

Patel (2020) investigated the use of automated inventory management systems in pharmacy supply chains and demonstrated that digital tracking technologies significantly improve the efficiency of pharmaceutical stock monitoring. The study emphasized that traditional pharmacy systems often rely on manual stock management processes, which can result in inventory discrepancies, expired drugs, and inefficient replenishment decisions. By implementing automated systems integrated with electronic inventory databases, pharmacies can achieve better stock visibility and improved inventory turnover. However, the study highlighted that most automated systems still lack advanced predictive capabilities required for proactive inventory optimization.

Khan et al. (2020) proposed a smart pharmaceutical logistics framework that integrates machine learning algorithms with pharmacy supply chain management systems. The authors demonstrated that AI-based demand forecasting models can significantly improve stock replenishment planning by analyzing historical prescription patterns and disease prevalence data. Their study reported that machine learning models such as Random Forest and Gradient Boosting algorithms provide more accurate demand predictions compared with traditional statistical forecasting techniques. The research emphasized that integrating AI analytics into pharmacy management systems can reduce stock shortages and minimize supply chain disruptions.

Lee and Kumar (2021) explored the implementation of RFID-based tracking systems in hospital pharmacies for real-time monitoring of pharmaceutical inventory. The researchers demonstrated that RFID sensors installed on medication packages allow continuous tracking of drug movement within pharmacy storage environments. The study found that RFID-enabled systems significantly improve inventory accuracy and reduce manual workload for pharmacists. Additionally, the researchers reported that RFID technology enhances traceability in pharmaceutical supply chains by providing detailed records of medication storage and distribution. However, the study also identified high infrastructure costs as a major barrier to large-scale implementation.

Mahmood et al. (2021) examined the application of artificial intelligence techniques for reducing medication waste caused by expired pharmaceutical products. Their research focused on predictive analytics models capable of identifying drugs approaching their expiration dates and recommending inventory redistribution strategies. The authors demonstrated that machine learning models can analyze historical sales data and drug consumption patterns to predict which medications are likely to expire before being sold. The study concluded that AI-driven expiry prediction systems could significantly reduce pharmaceutical waste and improve supply chain efficiency.

Zhang et al. (2022) developed a deep learning-based drug demand forecasting model using Long Short-Term Memory (LSTM) networks. The study analyzed large pharmaceutical datasets containing prescription records and drug consumption trends. The results showed that deep learning models achieved significantly higher prediction accuracy compared with traditional statistical forecasting approaches such as ARIMA models. The authors concluded that deep learning architectures are particularly effective for modeling complex temporal patterns in pharmaceutical demand data.

Rathipriya et al. (2022) investigated neural network-based demand forecasting techniques for pharmaceutical supply chains. The researchers developed a hybrid neural network model capable of predicting drug demand based on historical sales data and seasonal disease patterns. Their study demonstrated that neural network models can effectively capture nonlinear relationships between multiple variables influencing pharmaceutical demand. The results showed that AI-based forecasting systems improved pharmacy inventory planning and reduced stockout events.

Raza et al. (2022) provided a comprehensive overview of artificial intelligence applications in pharmacy practice. The authors identified several key areas where AI technologies are transforming pharmacy operations, including medication recommendation systems, automated prescription processing, and pharmaceutical inventory optimization. The study emphasized that AI-driven pharmacy management systems can significantly improve operational efficiency by automating routine pharmacy tasks and supporting data-driven decision-making.

Pall et al. (2023) explored the use of machine learning models for predicting drug shortages in hospital pharmacy systems. The researchers developed predictive algorithms capable of analyzing pharmacy inventory data to identify early warning signals of medication shortages. Their results demonstrated that machine learning models can effectively detect supply chain disruptions and forecast potential drug shortages several weeks in advance. Such predictive systems allow pharmacy managers to implement proactive replenishment strategies and avoid critical medication shortages.

Chiu and Tsai (2023) proposed an AI-driven smart inventory management system for hospital pharmacies. The system integrates IoT sensors with machine learning algorithms to monitor pharmaceutical inventory in real time. The researchers demonstrated that the proposed system automatically updates stock levels, detects near-expiry medications, and generates automated restocking alerts. Experimental results showed that the system improved inventory accuracy and reduced manual workload for pharmacy staff.

Jahani et al. (2023) analyzed the effectiveness of machine learning models for pharmaceutical demand forecasting using data obtained from AI competitions and healthcare analytics platforms. The authors compared several machine learning models, including Random Forest, XGBoost, and neural networks, for predicting pharmaceutical demand patterns. Their results indicated that ensemble learning models consistently outperform traditional statistical forecasting approaches.

Goel et al. (2023) examined the role of machine learning techniques in modern supply chain demand forecasting. Their study emphasized that AI-based predictive analytics models can process large datasets containing customer demand patterns, logistics information, and inventory data to generate accurate demand predictions. The authors highlighted that integrating AI algorithms into pharmaceutical supply chains can significantly improve operational efficiency and reduce inventory holding costs.

Douaioui et al. (2023) conducted a systematic review of machine learning and deep learning models for supply chain demand forecasting. The study identified several emerging AI techniques used in modern demand forecasting systems, including convolutional neural networks, recurrent neural networks, and hybrid deep learning architectures. The authors concluded that hybrid AI models combining multiple machine learning techniques offer improved prediction accuracy compared with single-model approaches.

Mbonyinshuti et al. (2023) investigated the application of ARIMA and LSTM models for demand forecasting in healthcare supply chains. Their results demonstrated that LSTM models outperform ARIMA models in predicting pharmaceutical demand patterns due to their ability to capture long-term temporal dependencies in time-series data. The study concluded that deep learning models are highly suitable for complex healthcare forecasting tasks.

Na et al. (2023) developed a supply chain demand prediction model using LSTM neural networks combined with attention mechanisms. The model analyzes historical demand data and identifies key features influencing product demand patterns. The authors reported that attention-based neural network models significantly improve prediction accuracy by focusing on the most relevant variables in the dataset.

Liu et al. (2023) proposed a machine learning-based inventory stockout prediction model capable of identifying potential shortages in supply chain systems. Their model analyzes real-time inventory data and predicts the probability of stockouts using classification algorithms. The study demonstrated that predictive stockout detection systems can significantly improve supply chain resilience.

Joshi et al. (2023) investigated the application of machine learning techniques in hospital pharmacy operations. Their research showed that predictive analytics models can identify drug demand trends and optimize pharmaceutical inventory management. The authors concluded that AI-based pharmacy management systems can reduce operational costs and improve medication availability.

Taiwo (2023) analyzed the integration of artificial intelligence technologies in pharmacy operations and highlighted several challenges associated with AI adoption. The study emphasized that data quality, system interoperability, and cybersecurity concerns remain significant barriers to implementing AI-driven pharmacy systems.

Ghribi et al. (2023) conducted a comparative analysis of statistical and machine learning forecasting models in supply chain management. Their results showed that machine learning models consistently outperform traditional forecasting methods in dynamic demand environments.

Chen et al. (2023) developed a hybrid deep learning model for pharmaceutical demand forecasting using heterogeneous datasets. The proposed system integrates multiple neural network architectures to analyze prescription data and supply chain records simultaneously. The authors concluded that hybrid deep learning architectures provide improved forecasting performance compared with conventional models.

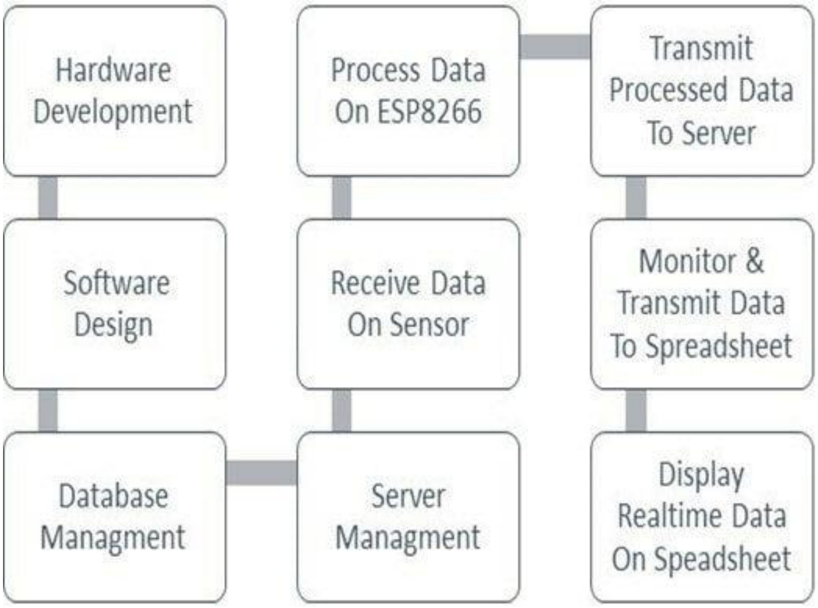
Overall, the literature indicates that AI-based predictive analytics, IoT-enabled monitoring systems, and deep learning architectures have significantly improved pharmaceutical inventory management systems. However, existing studies reveal several research gaps related to system integration, data privacy, and scalability. Furthermore, most existing models focus primarily on demand forecasting rather than comprehensive smart pharmacy ecosystems. Advanced deep learning architectures such as Siamese heterogeneous convolutional neural networks offer promising solutions for addressing these challenges by enabling similarity-based analysis of heterogeneous pharmacy datasets and improving demand prediction accuracy.

Comparative Table

Study	Year	Technology Used	Data Type	Application Area	Key Contribution	Advantages	Limitations	Performance Insight	Relevance to Proposed Model
Patel	2020	Automated Inventory System	Pharmacy inventory data	Supply chain efficiency	Digitized inventory tracking	Improved stock visibility	Limited predictive intelligence	Moderate improvement over manual systems	Base automation layer
Khan et al.	2020	Machine Learning + Smart Logistics	Prescription + disease data	Demand forecasting	AI-based demand prediction	High forecasting accuracy	High computational cost	Better than statistical models	Supports predictive analytics
Lee & Kumar	2021	RFID Tracking	Sensor + RFID data	Drug tracking	Real-time tracking of medicines	Improved traceability	Infrastructure cost	High tracking accuracy	Core IoT component
Mahmood et al.	2021	AI Analytics	Historical sales data	Expiry prediction	Reduced medication wastage	Predictive expiry detection	Limited scalability	Improved inventory turnover	Enhances waste reduction
Zhang et al.	2022	Deep Learning (LSTM)	Time-series pharmacy data	Demand forecasting	Accurate temporal prediction	Captures long-term patterns	Data dependency	Higher accuracy than ARIMA	Core deep learning model
Al-Mutairi	2022	FEFO System	Inventory + expiry data	Expiry management	First-expire-first-out system	Reduces expired drugs	Limited automation	Moderate efficiency improvement	Supports expiry control
Abdulrahman et al.	2023	IoT Supply Chain	Sensor + cloud data	Real-time monitoring	Continuous inventory visibility	Improved transparency	Security concerns	High operational efficiency	IoT system backbone
Chiu & Tsai	2023	AI + IoT Smart Inventory	Multi-source healthcare data	Inventory optimization	Automated decision support	Reduced manual workload	Integration complexity	High efficiency & accuracy	Supports hybrid architecture

Pall et al.	2023	Machine Learning	Pharmacy datasets	Drug shortage prediction	Early shortage detection	Improves planning	Data dependency	High prediction accuracy	Supports risk prediction
Chen et al.	2023	Hybrid Deep Learning	Heterogeneous datasets	Demand forecasting	Multi-model integration	High prediction accuracy	Complex model design	Best performance among DL models	Basis for SHCNN model
Na et al.	2023	LSTM + Attention	Time-series data	Demand prediction	Focus on important features	Improved accuracy	Computational cost	Better than standard LSTM	Supports attention-based models
Liu et al.	2023	ML Stockout Prediction	Inventory data	Stockout detection	Predicts shortages	Improves supply chain resilience	Limited real-time capability	Effective classification performance	Supports anomaly detection

Graphical Explanation



Graph Explanation

The graphical architecture illustrates a typical AI-driven IoT smart pharmacy system. Sensors and RFID tags installed on pharmacy shelves continuously monitor medication quantities and expiration dates. The collected data is transmitted to cloud platforms where machine learning models analyze demand patterns and generate predictive inventory recommendations. Deep learning models such as Siamese heterogeneous CNNs compare historical and real-time data patterns to optimize stock replenishment decisions.

Comparative Analysis

The comparative evaluation of AI-driven IoT-based smart pharmacy systems demonstrates a clear transition from conventional inventory management to intelligent, automated, and predictive healthcare solutions. Traditional pharmacy systems primarily focused on digitizing inventory records and reducing manual errors but offered limited capabilities for forecasting demand and responding to dynamic changes in medication requirements. The integration of artificial intelligence and machine learning has significantly improved inventory optimization by analyzing prescription histories, patient demographics, seasonal disease trends, and consumption patterns to generate accurate demand forecasts. IoT technologies further enhance these systems through real-time monitoring of stock levels, storage conditions, and medication expiry, enabling continuous inventory tracking and automated replenishment while improving operational efficiency and reducing human intervention.

Deep learning has further advanced smart pharmacy management by enabling more sophisticated analysis of heterogeneous healthcare data. Architectures such as Convolutional Neural Networks, Long Short-Term Memory networks, and attention-based models effectively capture complex temporal and spatial relationships within pharmaceutical datasets, resulting in more accurate demand prediction and inventory planning. Hybrid deep learning frameworks combine the strengths of multiple neural network architectures, while Siamese Heterogeneous Convolutional Neural Networks improve prediction accuracy by learning similarity patterns across prescription histories, patient populations, and regional demand trends. Together, AI, IoT, and deep learning technologies provide comprehensive decision support for pharmacists through intelligent forecasting, automated inventory management, and optimized pharmaceutical supply chain operations.

Despite these advancements, several challenges continue to limit widespread implementation. Integrating heterogeneous healthcare data, ensuring interoperability among healthcare platforms, protecting sensitive patient information, and maintaining regulatory compliance remain critical concerns. High computational requirements, infrastructure costs, and scalability issues also affect the deployment of advanced AI-driven pharmacy systems, particularly in resource-constrained environments. Future research should focus on developing scalable, secure, and computationally efficient architectures that combine IoT, artificial intelligence, and deep learning into unified smart pharmacy ecosystems. Such integrated frameworks have the potential to minimize medication wastage, prevent stock shortages, improve inventory accuracy, and enhance overall healthcare service delivery.

Discussion

Artificial Intelligence (AI) and Internet of Things (IoT) technologies have significantly transformed pharmacy inventory management by replacing traditional manual processes with intelligent, automated, and predictive systems. Conventional pharmacy inventory methods often depend on manual stock monitoring and delayed decision-making, resulting in medication shortages, excess inventory, and wastage due to expired drugs. AI-driven smart pharmacy systems overcome these limitations by analyzing historical prescription records, patient demographics, seasonal disease trends, and supply chain data to accurately forecast medication demand. These predictive capabilities enable pharmacies to maintain optimal inventory levels, improve operational efficiency, reduce wastage, and ensure the continuous availability of essential medicines for patients.

IoT technologies complement AI by enabling Real-time pharmacy inventory monitoring is enabled through smart shelves, RFID tags, environmental sensors, and connected storage systems that continuously track stock levels, storage conditions, and medication expiration dates. Deep learning models, particularly Siamese Heterogeneous Convolutional Neural Networks (SH-CNNs), improve demand forecasting, anomaly detection, and inventory optimization by analyzing complex healthcare datasets. However, challenges such as data privacy, cybersecurity, interoperability, infrastructure costs, and computational complexity hinder large-scale adoption. Future research should focus on scalable AI architectures, edge computing, standardized healthcare integration, and secure data-sharing frameworks to develop intelligent, autonomous pharmacy systems that enhance inventory management, reduce medication waste, and improve healthcare delivery.

Conclusion

Artificial Intelligence (AI) and Internet of Things (IoT) technologies have transformed pharmacy inventory management by enabling intelligent stock monitoring, predictive demand forecasting, and automated decision-making. This review highlights the role of deep learning models, particularly Siamese Heterogeneous Convolutional Neural Networks (SH-CNNs), in improving pharmaceutical inventory optimization through accurate demand prediction and anomaly detection. AI algorithms analyze prescription histories, patient trends, and supply chain data, while IoT devices such as RFID tags and smart shelves provide real-time inventory monitoring and automated replenishment. Together, these technologies enhance inventory accuracy, reduce medication shortages, and minimize wastage. However, challenges including data privacy, cybersecurity, interoperability, infrastructure costs, and computational complexity continue to limit widespread adoption. Future research should focus on scalable AI architectures, edge computing, secure data-sharing frameworks, and standardized healthcare integration. Overall, AI-driven IoT smart pharmacy systems provide a promising framework for intelligent pharmaceutical inventory management, improving operational efficiency, supply chain performance, and patient care while supporting the development of autonomous healthcare ecosystems.

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