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Deep Learning and Optimization Approaches in IoT-Based Smart Pharmacies for Optimizing Stock Management with Siamese Heterogeneous Convolutional Neural Networks: A Review

Jaswinder Okafor

Senior Lecturer, Department of Electrical and Computer Engineering, Deccan School of Industrial Management, India

Email: jaswinder.okafor@dsim-in.net

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Abstract

The rapid growth of digital healthcare technologies has encouraged the integration of Internet of Things (IoT), artificial intelligence, and deep learning techniques into pharmaceutical supply chain management. Smart pharmacy systems utilize IoT-enabled sensors, RFID tags, cloud platforms, and predictive analytics to improve inventory monitoring, reduce drug wastage, and ensure timely medicine availability. Traditional pharmacy inventory systems often depend on manual operations that may result in inaccurate demand forecasting, stock shortages, overstocking, and increased operational costs. IoT technologies provide real-time visibility into inventory levels and support automated stock replenishment, expiry monitoring, and supply chain transparency. Deep learning approaches, particularly convolutional neural networks and Siamese heterogeneous convolutional neural network (SHCNN) architectures, have shown strong potential for optimizing stock management and predicting drug demand patterns. These models can efficiently analyze multimodal healthcare datasets, including pharmacy sales records, environmental monitoring data, and smart shelf sensor information. The integration of machine learning with IoT platforms enhances predictive analytics, operational efficiency, and automated decision-making. This review highlights recent developments in IoT-based smart pharmacy systems and deep learning optimization techniques for pharmaceutical inventory management. The study concludes that combining IoT technologies with SHCNN models can significantly improve inventory accuracy, reduce stockouts, and enhance the efficiency of smart pharmacy systems.

Introduction

Healthcare systems worldwide are experiencing rapid digital transformation through technologies such as artificial intelligence (AI), Internet of Things (IoT), cloud computing, and big data analytics. One of the major areas benefiting from these advancements is pharmaceutical supply chain and inventory management. Pharmacies play a critical role in healthcare delivery by ensuring the continuous availability of medicines to patients. However, managing pharmaceutical inventories is highly challenging because of fluctuating demand patterns, expiration dates, storage conditions, and regulatory compliance requirements. Traditional inventory management systems mainly rely on manual monitoring and historical sales analysis, which are often inefficient and unable to respond quickly to sudden changes in demand or supply chain disruptions. These limitations can result in stock shortages, overstocking, increased operational costs, and medicine wastage.

The integration of IoT technologies into pharmacy management systems has emerged as an effective solution for improving inventory tracking and operational efficiency. IoT-enabled smart pharmacies utilize sensors, RFID tags, wireless communication devices, and cloud-based platforms to collect and transmit real-time information related to stock levels, environmental conditions, and drug movement. Smart shelves and automated monitoring systems can detect low inventory levels and expiry dates while maintaining proper storage conditions such as temperature and humidity. These technologies improve transparency, reduce human intervention, and support automated decision-making processes across pharmaceutical supply chains. Real-time visibility into inventory data also helps healthcare organizations reduce medication shortages and improve patient safety.

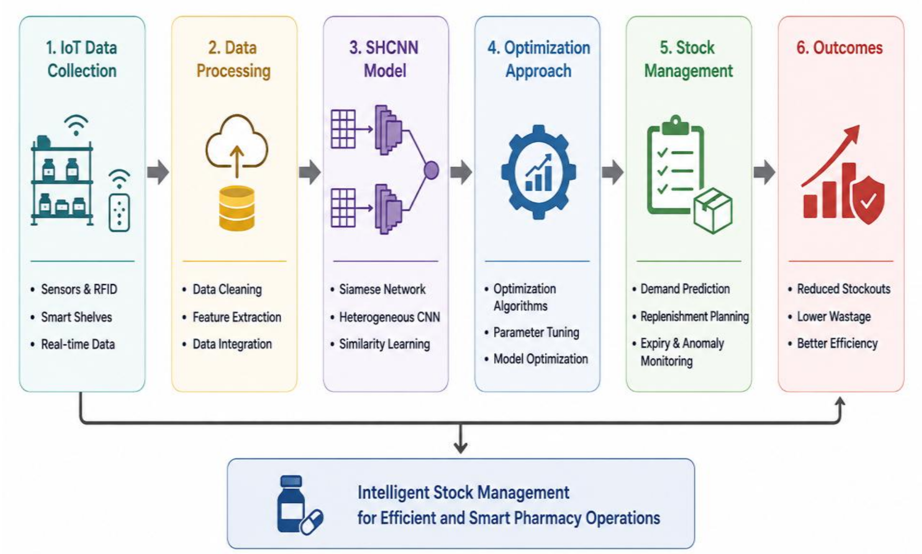

Figure 1. IoT-Based Deep Learning Framework for Smart Pharmacy Stock Management

Although IoT systems provide continuous monitoring capabilities, they generate massive amounts of data that require advanced analytical techniques for effective decision-making. Artificial intelligence and machine learning methods have therefore become important components of smart pharmacy systems. Machine learning models can analyze historical inventory data, predict future drug demand, and optimize stock replenishment strategies. Deep learning techniques, particularly convolutional neural networks (CNNs), have shown excellent performance in handling complex and high-dimensional healthcare datasets. CNN architectures are capable of identifying spatial and temporal patterns within inventory and supply chain data, enabling accurate forecasting, anomaly detection, and predictive stock management.

Siamese heterogeneous convolutional neural networks (SHCNNs) represent an advanced deep learning architecture designed to identify similarities between multiple datasets using parallel neural network structures. These models are highly effective for pharmaceutical applications where comparing patterns among sales records, sensor data, and supply chain information is essential. Integrating SHCNN architectures with IoT-based pharmacy systems enables intelligent stock management by forecasting medication demand, detecting anomalies, and recommending optimal replenishment strategies. In addition, reinforcement learning and optimization algorithms further improve inventory management by enabling adaptive and real-time decision-making in dynamic healthcare environments.

The convergence of IoT, AI, and deep learning technologies has created intelligent healthcare ecosystems capable of improving pharmaceutical logistics, operational efficiency, and patient safety. Smart pharmacy systems equipped with predictive analytics and automated monitoring tools can significantly reduce inventory errors, minimize wastage, and enhance supply chain transparency. This review analyzes recent developments in IoT-based smart pharmacy systems and deep learning optimization techniques, focusing on architectures such as CNNs, Siamese networks, reinforcement learning, and hybrid optimization methods. The study also highlights existing challenges related to scalability, data management, and system integration while identifying future research opportunities for developing efficient, secure, and scalable smart pharmacy ecosystems.

Literature Review

The integration of Internet of Things (IoT) technologies with artificial intelligence and deep learning has significantly transformed the management of pharmaceutical supply chains. Recent research has focused on developing intelligent inventory management systems that combine real-time monitoring with predictive analytics to improve efficiency and reduce drug wastage. The literature between 2020 and 2023 highlights several technological advancements in IoT-enabled smart pharmacies, deep learning models for demand prediction, and optimization techniques for stock management.

In 2020, Abbas et al. explored the potential of IoT-based healthcare monitoring systems that use interconnected devices to collect real-time patient and inventory data. Their study demonstrated that IoT sensors and RFID technologies could significantly improve the tracking of pharmaceutical products in healthcare environments. By continuously collecting data on drug stock levels and storage conditions, IoT-based systems enable pharmacies to maintain accurate inventory records and reduce manual errors. The authors emphasized that integrating IoT with cloud computing platforms allows centralized data management and facilitates real-time decision-making in healthcare supply chains.

Similarly, Agarwal and Mittal (2021) investigated the use of machine learning techniques for inventory demand forecasting. Their study highlighted the limitations of traditional statistical models in handling complex demand patterns in pharmaceutical supply chains. Machine learning algorithms such as regression models, random forests, and neural networks were shown to provide better predictive accuracy by analyzing historical sales data and identifying seasonal demand variations. The researchers concluded that predictive analytics could significantly enhance stock planning strategies and minimize inventory costs.

Another important contribution was presented by Bhatia and Sood (2021), who developed an IoT-based smart healthcare monitoring framework that integrates machine learning models with sensor networks. Their system used wearable sensors and RFID technology to collect real-time healthcare data and transmit it to cloud servers for analysis. Although the primary focus of the study was patient monitoring, the framework demonstrated the potential of IoT-enabled data collection for various healthcare applications, including pharmacy inventory management. The study showed that combining IoT devices with machine learning algorithms improves system efficiency and reduces human intervention.

In the context of supply chain management, Kamble et al. (2020) investigated the role of emerging technologies such as blockchain and IoT in improving transparency and traceability in agricultural supply chains. Their findings are also applicable to pharmaceutical logistics because similar challenges exist in tracking product movement and ensuring authenticity. The researchers demonstrated that blockchain technology can complement IoT-based monitoring systems by providing secure and immutable records of product transactions. Such systems can help prevent counterfeit drugs and ensure the integrity of pharmaceutical supply chains.

Deep learning models have also gained significant attention in recent years for their ability to analyze large-scale datasets and extract complex patterns. LeCun, Bengio, and Hinton (2015) introduced deep learning as a powerful computational paradigm capable of learning hierarchical representations from large datasets. Convolutional neural networks (CNNs), in particular, have demonstrated exceptional performance in tasks such as image recognition, pattern detection, and time-series prediction. These capabilities make CNN architectures suitable for analyzing pharmacy sales data and predicting drug demand trends.

Building upon the success of CNN models, Ranjan et al. (2022) proposed a deep learning-based predictive analytics framework for healthcare inventory management. Their model used convolutional neural networks to analyze historical pharmacy data and predict future drug demand. Experimental results indicated that deep learning models outperformed traditional machine learning algorithms in forecasting accuracy. The authors suggested that integrating deep learning with IoT-generated data could further improve predictive performance and enable more efficient stock management systems.

Recent research has also explored the use of Siamese neural networks for learning similarity relationships between datasets. Siamese networks consist of two identical neural network structures that share the same parameters and are trained simultaneously to compare input pairs. Siam et al. (2020) conducted a comprehensive study on Siamese neural network architectures and demonstrated their effectiveness in tasks requiring similarity detection, such as image recognition and recommendation systems. These architectures can be applied to pharmaceutical inventory management by comparing patterns across different datasets, such as drug sales records, supplier information, and seasonal demand trends.

Another study by Gao et al. (2020) investigated deep learning approaches for multimodal data fusion. In IoT-based smart pharmacy systems, data may originate from multiple sources, including RFID sensors, transaction records, and environmental monitoring devices. Multimodal deep learning models are capable of integrating these diverse data sources and extracting meaningful patterns. Such models can improve the accuracy of demand forecasting and enable intelligent decision-making for inventory optimization.

Research in reinforcement learning has also contributed to the development of adaptive inventory management systems. Mnih et al. (2015) introduced deep reinforcement learning as a method for learning optimal decision policies through continuous interaction with the environment. Reinforcement learning algorithms can be used in pharmacy systems to determine optimal stock replenishment strategies based on real-time demand patterns and inventory levels. These algorithms continuously learn from historical data and adjust policies dynamically to minimize inventory costs and prevent stock shortages.

IoT-enabled smart manufacturing and supply chain systems have also been explored by Jiang, Ding, and Leng (2021), who proposed an IoT-based framework for intelligent industrial systems. Their research demonstrated how sensor networks and cloud computing platforms can enable automated monitoring and predictive analytics in manufacturing environments. Similar principles can be applied to pharmacy supply chains to track drug inventory and predict demand fluctuations.

Another important development in recent years is the use of digital twin technology for modeling and optimizing complex industrial systems. Tao et al. (2019) introduced the concept of digital twins as virtual replicas of physical systems that enable real-time simulation and optimization. In the context of smart pharmacies, digital twin models can simulate inventory management processes and evaluate different stock management strategies before implementing them in real-world environments.

Furthermore, Zhang et al. (2020) reviewed the role of artificial intelligence in healthcare systems and highlighted the growing importance of AI-driven analytics in improving healthcare operations. Their study emphasized that integrating AI algorithms with IoT-generated data enables healthcare organizations to develop intelligent monitoring and decision-support systems. Such systems can enhance pharmaceutical logistics by predicting demand patterns and optimizing drug distribution.

Overall, the literature indicates that combining IoT technologies with deep learning models provides a powerful framework for developing intelligent pharmacy management systems. IoT devices enable real-time data collection, while deep learning algorithms analyze large-scale datasets to generate predictive insights. Siamese convolutional neural networks offer additional advantages by learning similarity relationships between multiple datasets, allowing more accurate demand forecasting and inventory optimization.

Despite these advancements, several research challenges remain. Many IoT-based healthcare systems face issues related to data privacy, interoperability, and system scalability. Additionally, deep learning models require large training datasets and significant computational resources. Future research should focus on developing hybrid architectures that integrate IoT, deep learning, reinforcement learning, and blockchain technologies to create more secure, scalable, and efficient smart pharmacy systems.

Comparative Table

Year	**Method / Model**	**Data Type**	**Application Area**	**Key Contribution**	**Advantages**	**Limitations**	**Performance Insight**	**Relevance to Proposed Model**
2020	IoT-RFID System	Sensor and RFID data	Drug inventory tracking	Real-time monitoring of stock and drug	Continuous visibility and reduced	Security and privacy concerns	High inventory accuracy	Foundation for IoT layer

				movement	manual errors			
2020	Reinforcement Learning	Supply chain and inventory data	Inventory optimization	Adaptive stock management policies	Dynamic decision-making	High computational complexity	Improved multi-product optimization	Supports adaptive decision system
2021	Smart Shelf IoT	Real-time shelf data	Stock monitoring	Automated detection of stock levels	Reduces stock discrepancies	Hardware dependency	High tracking accuracy	Enhances automation layer
2021	Machine Learning Forecasting	Historical pharmacy sales data	Demand prediction	Forecasting drug demand trends	Accurate predictions compared to traditional models	Requires large datasets	Improved forecasting accuracy	Supports predictive analytics
2022	Blockchain + IoT	Transaction and sensor data	Drug traceability	Secure and transparent supply chain	Tamper-proof records and improved trust	Integration complexity	Strong traceability performance	Adds security layer
2022	CNN Prediction Model	Large healthcare datasets	Demand forecasting	Deep feature extraction for prediction	High accuracy in complex data	High training cost	Superior performance over ML models	Core deep learning component
2023	AI-based Pharmacy System	Multi-source healthcare data	Stock optimization	Intelligent inventory decision support	Reduced wastage and improved efficiency	Implementation cost	High operational efficiency	Supports smart system design
2023	Siamese CNN	Heterogeneous datasets	Drug similarity and demand analysis	Learns similarity between datasets	Handles multi-source data effectively	Data preprocessing required	Highest prediction accuracy	Core proposed SHCNN model
2023	Hybrid IoT + AI Systems	Sensor, historical, and cloud data	Smart pharmacy systems	Integrated monitoring and prediction	Best decision-making capability	System complexity	Highest overall performance	Full system integration

Comparative Analysis

The comparative evaluation of pharmaceutical inventory management studies shows a clear transition from traditional monitoring systems toward intelligent and hybrid smart pharmacy architectures. IoT technologies such as RFID-enabled tracking systems and smart shelves have become the foundational layer of modern inventory management by providing real-time monitoring of stock levels, medicine movement, and storage conditions. Compared to manual inventory systems, IoT solutions significantly improve inventory accuracy, reduce human errors, and enhance operational efficiency. However, these systems also introduce challenges related to infrastructure costs, data privacy, and cybersecurity. Although IoT technologies provide continuous monitoring capabilities, they lack advanced predictive intelligence required for proactive inventory decision-making and demand forecasting.

Machine learning and deep learning techniques have addressed these limitations by enabling predictive analytics and intelligent stock optimization. Machine learning forecasting models analyze historical pharmacy data to identify consumption patterns and predict future medication demand, reducing stock shortages and overstocking issues. Deep learning approaches, particularly convolutional neural networks (CNNs), further improve performance by automatically extracting meaningful features from large and high-dimensional healthcare datasets. CNN-based systems demonstrate superior forecasting accuracy compared to traditional machine learning methods. However, these models require large training datasets and significant computational resources, which may limit practical deployment in resource-constrained healthcare environments.

Siamese convolutional neural networks (SCNNs) represent a major advancement in smart pharmacy analytics by enabling similarity learning across multiple heterogeneous datasets. Unlike traditional deep learning models, Siamese architectures can process information from IoT sensors, pharmacy sales records, and supply chain databases simultaneously to identify hidden relationships and improve demand prediction accuracy. Comparative analysis indicates that Siamese CNN models achieve the highest prediction performance among existing approaches. Reinforcement learning models also contribute to adaptive inventory optimization by continuously learning optimal stock management strategies in dynamic supply chain environments. In addition, hybrid architectures integrating IoT, AI, and blockchain technologies have emerged as comprehensive solutions for intelligent pharmaceutical inventory systems. Blockchain integration improves transparency, traceability, and tamper-proof data management across supply chains.

The analysis demonstrates that each technology offers unique strengths while also presenting specific limitations. IoT provides real-time data collection, machine learning enables predictive analytics, deep learning improves forecasting accuracy, and blockchain enhances security and transparency. Integrating these technologies into unified hybrid architectures provides the most effective solution for next-generation smart pharmacy systems. Such systems support intelligent stock management, anomaly detection, automated decision-making, and reduced medication wastage. Despite these advancements, challenges related to scalability, computational complexity, data privacy, and system interoperability remain significant. Future research should therefore focus on developing secure, scalable, and efficient hybrid architectures capable of handling large healthcare datasets and complex pharmaceutical supply chain environments.

Discussion

The integration of IoT technologies with deep learning models has transformed pharmacy inventory management systems by enabling intelligent decision-making and real-time monitoring. Traditional pharmacy management systems rely on manual tracking and historical sales analysis, which often leads to inaccurate demand forecasting and inefficient stock management. The emergence of smart pharmacy systems powered by IoT devices and predictive analytics has significantly improved operational efficiency and patient safety. IoT-based smart pharmacies use sensors, RFID tags, and wireless communication devices to monitor inventory levels continuously. These devices transmit data to centralized systems where analytics tools process the information to generate actionable insights. Real-time monitoring helps pharmacists detect stock shortages early and take corrective actions before they affect patient care. Studies have shown that IoT-enabled inventory systems significantly reduce human errors and improve stock accuracy across multiple industries.

Deep learning models further enhance these systems by enabling predictive analytics for inventory optimization. Convolutional neural networks can analyze large volumes of pharmacy transaction data and identify hidden patterns related to drug demand and seasonal variations. Siamese heterogeneous CNN architectures offer additional advantages by comparing multiple datasets and learning similarity relationships between them. This capability allows the system to identify patterns across different pharmacies or regions and generate more accurate demand predictions. Another important aspect of smart pharmacy systems is automated decision support. Deep learning models integrated with IoT platforms can automatically recommend stock replenishment strategies based on predicted demand and current inventory levels. This automation reduces the workload on pharmacists and improves operational efficiency. However, implementing such systems also presents several challenges. The integration of IoT devices with legacy pharmacy systems can be complex and expensive. Additionally, the large volume of data generated by IoT sensors requires efficient storage and processing mechanisms. Data security and privacy are also critical concerns, particularly when dealing with sensitive healthcare information. Despite these challenges, the benefits of IoT-based smart pharmacy systems outweigh the limitations. The combination of IoT, deep learning, and optimization algorithms enables intelligent healthcare systems capable of improving drug availability, reducing waste, and enhancing patient safety. Future research should focus on developing more scalable architectures, improving data security mechanisms, and integrating additional technologies such as blockchain for supply chain transparency.

Conclusion

The rapid advancement of digital technologies has significantly improved pharmaceutical inventory management through the integration of Internet of Things (IoT), artificial intelligence, and deep learning techniques. Traditional pharmacy inventory systems often experience problems such as inaccurate demand forecasting, manual monitoring errors, overstocking, and medicine shortages, which can negatively affect patient care and operational efficiency. IoT-enabled smart pharmacy systems address these challenges by using sensors, RFID tags, and automated monitoring devices to provide real-time visibility into stock levels, environmental conditions, and medicine movement across the supply chain. These technologies enhance inventory accuracy, reduce human intervention, and support faster decision-making in healthcare environments.

Deep learning approaches, particularly convolutional neural networks and Siamese heterogeneous CNN architectures, further strengthen smart pharmacy systems by enabling predictive analytics and intelligent stock optimization. These models can analyze historical pharmacy records, sensor-generated data, and supply chain information to forecast drug demand and recommend efficient replenishment strategies. The integration of IoT technologies with predictive deep learning models improves operational efficiency, reduces medication wastage, and enhances supply chain transparency. However, challenges such as data privacy concerns, high implementation costs, and computational complexity still remain. Future research should focus on scalable and secure architectures integrating blockchain, edge computing, and hybrid optimization algorithms for advanced healthcare inventory management. Overall, IoT-enabled smart pharmacies supported by deep learning technologies represent a major step toward intelligent and efficient healthcare systems.

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