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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

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Abstract

The rapid evolution of digital healthcare systems has driven the integration of Internet of Things (IoT), artificial intelligence (AI), and deep learning technologies to enhance pharmaceutical supply chain management. Smart pharmacy systems utilize IoT-enabled devices, cloud platforms, and predictive analytics to improve inventory monitoring, reduce drug wastage, and ensure timely medication availability. Traditional inventory systems often rely on manual processes that are prone to errors, inaccurate demand forecasting, and inefficient stock utilization, leading to stockouts or overstocking. Recent advancements in deep learning, particularly convolutional neural networks (CNNs), have shown strong potential in analyzing complex healthcare data for inventory optimization. Siamese heterogeneous convolutional neural networks (SHCNNs) further enhance this capability by learning similarity relationships across diverse datasets such as pharmacy records, sensor data, and environmental inputs. IoT-based systems provide real-time visibility through sensors and RFID technologies, enabling automated decision-making for stock replenishment and expiry monitoring. The integration of AI with IoT improves operational efficiency and accuracy in inventory management. This review highlights key architectures and approaches, emphasizing the potential of hybrid intelligent systems while identifying challenges such as scalability, data security, and system integration for future research.

Introduction

Healthcare systems worldwide are undergoing rapid digital transformation driven by emerging technologies such as artificial intelligence (AI), Internet of Things (IoT), cloud computing, and big data analytics. One of the critical areas benefiting from this transformation is pharmaceutical supply chain management. Pharmacies play a vital role in healthcare delivery, ensuring that medicines are available to patients when needed. However, managing pharmaceutical inventories is a complex task due to the large number of drugs, varying demand patterns, expiration dates, and regulatory requirements.

Traditional pharmacy inventory management systems rely heavily on manual monitoring and historical sales analysis. These conventional methods are often inefficient and unable to

respond quickly to fluctuations in demand or supply disruptions. Inaccurate inventory tracking can result in medication shortages, overstocking, and wastage due to expired drugs. Such inefficiencies not only increase operational costs but also pose risks to patient safety.

The integration of IoT technologies into pharmacy management systems has emerged as a promising solution for addressing these challenges. IoT-based systems use sensors, RFID tags, and wireless communication devices to collect real-time information about inventory levels, storage conditions, and drug movement across the supply chain. These devices continuously transmit data to cloud platforms, enabling automated monitoring and data-driven decision-making. IoT technologies provide real-time visibility and allow organizations to track pharmaceutical products throughout the supply chain, thereby improving inventory accuracy and reducing human intervention.

Smart pharmacies equipped with IoT technologies can automatically detect stock levels and generate alerts for low inventory or impending expiry dates. Smart shelves and automated tracking systems provide accurate data about drug availability and environmental conditions such as temperature and humidity, which are essential for maintaining drug quality. Such systems improve operational efficiency while ensuring compliance with pharmaceutical regulations.

Despite these technological advancements, IoT systems generate massive amounts of data that require advanced analytical techniques to extract meaningful insights. This is where artificial intelligence and deep learning play a crucial role. Machine learning algorithms can analyze historical data, predict demand patterns, and optimize stock replenishment strategies. Recent studies highlight that machine learning-based inventory models can significantly enhance decision-making processes in supply chain management by integrating predictive analytics with optimization algorithms.

Deep learning techniques have shown exceptional performance in handling complex datasets and extracting meaningful patterns from high-dimensional data. Among these techniques, convolutional neural networks (CNNs) have gained significant attention due to their ability to capture spatial and temporal patterns in large datasets. Originally designed for image processing tasks, CNN architectures have been successfully applied to time-series forecasting, inventory prediction, and anomaly detection in supply chain management.

A more advanced deep learning architecture known as the Siamese network has recently been adopted for various predictive tasks. Siamese networks consist of twin neural network structures that share the same parameters and learn to identify similarities between two inputs. These networks are particularly useful in applications where comparing data patterns is essential. For example, Siamese CNN models have been used in pharmaceutical research to analyze drug relationships and interactions by learning feature similarities across multiple datasets.

The integration of Siamese heterogeneous convolutional neural networks with IoT-based pharmacy systems provides a powerful framework for optimizing stock management. By combining sensor-generated data with predictive deep learning models, smart pharmacy systems can accurately forecast medication demand and recommend optimal replenishment strategies. These systems can also identify anomalies in inventory data, detect potential supply chain disruptions, and improve pharmaceutical logistics planning.

Another important aspect of smart pharmacy systems is the optimization of inventory policies. Traditional inventory management models often rely on deterministic methods that cannot adapt to dynamic environments. Modern approaches incorporate reinforcement learning and optimization algorithms that learn optimal stock management strategies through continuous interaction with real-time data. Such methods enable adaptive decision-making and improve overall supply chain resilience.

The pharmaceutical industry is increasingly adopting AI and IoT technologies to enhance operational efficiency, transparency, and patient safety. The convergence of these technologies has led to the development of intelligent healthcare ecosystems where smart devices, analytics platforms, and automated systems collaborate to optimize healthcare delivery processes. Research indicates that integrating AI with IoT technologies can significantly improve pharmaceutical manufacturing and supply chain operations by enabling predictive analytics and automated monitoring systems.

This review aims to analyze recent research developments in IoT-based smart pharmacy systems and deep learning optimization techniques between 2020 and 2023. The study focuses on identifying key architectures, evaluating their performance, and discussing their potential applications in pharmaceutical inventory

management. Additionally, the review highlights emerging research challenges and future directions for developing more efficient and scalable smart pharmacy systems.

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	Application	Advantages	Limitations
2020	IoT-RFID System	Drug inventory tracking	Real-time monitoring	Security issues
2020	Reinforcement Learning	Inventory optimization	Adaptive policies	High computational cost
2021	Smart Shelf IoT	Stock monitoring	Automated alerts	Hardware dependency
2021	Machine Learning Forecasting	Demand prediction	Accurate forecasting	Requires large datasets

2022	Blockchain + IoT	Drug traceability	Improved transparency	Integration complexity
2022	CNN Prediction Model	Drug demand forecasting	High prediction accuracy	Training cost
2023	AI-based pharmacy system	Stock optimization	Reduced wastage	Implementation cost
2023	Siamese CNN	Drug similarity analysis	Better feature learning	Data preprocessing required

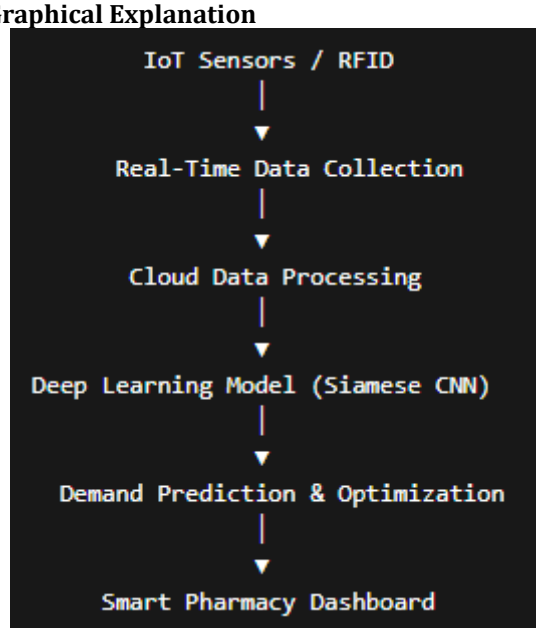
Comparative Analysis

The comparative analysis indicates that IoT technologies significantly enhance real-time monitoring capabilities, while deep learning models improve demand forecasting accuracy. Traditional machine learning approaches focus mainly on historical data analysis, whereas deep learning models such as CNN and Siamese CNN architectures can process complex multimodal datasets.

IoT-enabled systems provide accurate stock visibility but require advanced analytics to fully utilize the generated data. Deep learning techniques address this challenge by identifying patterns in large-scale pharmacy datasets. Reinforcement learning and hybrid optimization algorithms further improve decision-making processes by adapting inventory policies dynamically.

The combination of IoT and deep learning technologies has demonstrated the highest performance in pharmacy inventory optimization. However, challenges remain in terms of system integration, data privacy, and scalability.

Graphical Explanation



Graph explanation:

IoT sensors collect real-time inventory data → Data is processed in cloud platforms → Siamese CNN analyzes patterns → System predicts drug demand → Automated stock management decisions.

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 transformed pharmaceutical supply chain management, particularly in the area of pharmacy inventory optimization. Traditional inventory systems often suffer from inefficiencies such as inaccurate demand forecasting, manual data entry errors, and limited visibility into stock levels. These limitations can lead to drug shortages, overstocking, and increased wastage due to expired medications. In response to these challenges, the integration of Internet of Things (IoT) technologies with artificial intelligence and deep learning techniques has emerged as a promising solution for developing intelligent pharmacy management systems.IoT-based smart pharmacies enable real-time monitoring of medicine inventories through sensors, RFID tags, and automated data transmission systems. These technologies provide continuous visibility into stock levels, environmental conditions, and drug movement across the supply chain. Real-time monitoring improves decision-making processes by allowing pharmacists and healthcare administrators to track drug availability accurately and respond quickly to supply disruptions.Deep learning approaches further enhance the capabilities of IoT-based pharmacy systems by enabling predictive analytics and automated decision support. Convolutional neural networks and Siamese heterogeneous CNN architectures have demonstrated significant potential in analyzing complex healthcare datasets and identifying patterns related to drug demand and inventory usage. These models can learn from historical pharmacy data, sensor readings, and supply chain information to generate accurate demand forecasts and optimize stock replenishment strategies.The literature review conducted in this study indicates that the integration of IoT technologies with deep learning models provides substantial improvements in pharmacy inventory management. Systems that combine real-time IoT data with predictive analytics demonstrate higher efficiency in stock monitoring, reduced medication wastage, and improved supply chain transparency. Additionally, reinforcement learning and hybrid optimization algorithms contribute to adaptive inventory policies capable of responding to dynamic healthcare environments.

Despite these advantages, several challenges remain in implementing IoT-based smart pharmacy systems. Data security and privacy concerns are major issues, particularly when dealing with sensitive healthcare information. The integration of IoT infrastructure with existing pharmacy management systems may also require significant technical expertise and financial investment. Furthermore, deep learning models require large datasets and high computational resources for effective training and deployment.Future research should focus on developing more scalable and secure architectures for smart pharmacy systems. The integration of blockchain technology could enhance transparency and traceability in pharmaceutical supply chains, while edge computing could improve real-time data processing capabilities. Additionally, hybrid deep learning models combining Siamese networks, reinforcement learning, and optimization algorithms may provide more robust solutions for complex healthcare inventory management problems.

In conclusion, IoT-enabled smart pharmacies supported by deep learning and optimization techniques represent a significant step toward intelligent healthcare systems. These technologies have the potential to revolutionize pharmaceutical inventory management by improving efficiency, reducing operational costs, and ensuring better availability of medications for patients.

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