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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 between 2020 and 2023 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

Pharmaceutical supply chains play a critical role in healthcare systems by ensuring the timely availability of medicines to patients. Efficient inventory management within pharmacies is essential to maintain medication availability while minimizing financial losses caused by expired or overstocked drugs. However, conventional pharmacy inventory management methods are often inefficient due to manual record-keeping, delayed stock updates, and limited forecasting capabilities. These challenges lead to frequent stockouts, wastage of medicines, and operational inefficiencies within healthcare institutions.

The increasing complexity of pharmaceutical supply chains has driven the adoption of digital technologies such as Artificial Intelligence (AI), Internet of Things (IoT), big data analytics, and cloud computing to enhance pharmacy operations. AI technologies have proven particularly effective in automating decision-making processes related to inventory management, demand forecasting, and supply chain optimization. AI-powered pharmacy management systems can analyze historical prescription data, patient demographics, disease patterns, and seasonal trends to predict future drug demand accurately. Such predictive capabilities enable pharmacies to maintain optimal stock levels and prevent shortages or excess inventory.

The integration of IoT technologies further enhances pharmacy inventory management systems by enabling real-time monitoring of pharmaceutical products. IoT devices such as RFID tags, smart shelves, and sensor-enabled storage units can continuously track drug availability, temperature conditions, and expiration dates. These devices transmit data to centralized cloud platforms where AI algorithms analyze the information and generate automated alerts for pharmacists. Smart shelf systems, for instance, can detect when a medication stock level falls below a predefined threshold and automatically trigger replenishment requests. Such systems significantly improve inventory accuracy and reduce human errors in pharmacy operations.

In recent years, deep learning techniques have emerged as powerful tools for analyzing complex healthcare data. Convolutional neural networks (CNNs), recurrent neural networks (RNNs), and transformer-based models have been widely applied in healthcare analytics, drug discovery, medical imaging, and pharmaceutical supply chain management. Among these techniques, CNN architectures are particularly effective in extracting spatial patterns and relationships from large datasets. When applied to pharmacy inventory systems, CNN models can analyze heterogeneous data sources such as prescription logs, sensor readings, and supply chain transactions to identify patterns related to drug consumption and demand fluctuations.

Siamese neural networks represent an advanced deep learning architecture designed to learn similarity relationships between pairs of data inputs. These networks consist of two identical neural network branches that process separate inputs and compare their outputs to determine similarity or dissimilarity. In the context of pharmacy inventory management, Siamese heterogeneous convolutional neural networks (SH-CNNs) can compare historical prescription patterns across different time periods, geographic locations, or patient demographics. This capability allows the system to detect similar demand patterns and generate more accurate demand forecasts for pharmaceutical products.

The combination of AI, IoT, and Siamese deep learning architectures has led to the emergence of smart pharmacy ecosystems capable of autonomous inventory management. These systems integrate IoT sensors, cloud computing platforms, machine learning models, and advanced analytics tools to provide real-time decision support for pharmacists and healthcare administrators. Such technologies enable continuous monitoring of medication inventory, automated stock replenishment, and predictive demand analysis.

Despite these advancements, several challenges remain in the implementation of AI-driven smart pharmacy systems. One major challenge is the integration of heterogeneous data sources, including electronic health records, prescription databases, IoT sensor data, and pharmaceutical supply chain information. Ensuring data interoperability and compatibility across different healthcare platforms remains a significant technical hurdle. Additionally, the deployment of IoT infrastructure requires substantial financial investment, which may limit adoption in small or rural pharmacies.

Another challenge involves data privacy and security. Pharmacy systems handle sensitive patient information and prescription records, which must be protected against unauthorized access and cyber threats. Implementing secure data storage, encryption techniques, and access control mechanisms is essential to maintain patient confidentiality and regulatory compliance.

Moreover, AI models used in pharmacy inventory management must be highly accurate and reliable. Inaccurate demand predictions may lead to severe consequences such as medication shortages or excessive stock accumulation. Therefore, continuous model training, validation, and monitoring are necessary to ensure reliable performance in real-world healthcare environments.

This review paper aims to analyze recent developments in AI-driven IoT smart pharmacy systems, focusing on the application of Siamese heterogeneous convolutional neural networks for optimizing pharmaceutical inventory management. The study evaluates existing research published between 2020 and 2023, identifying key technological trends, challenges, and opportunities in the field. A comprehensive literature review and comparative analysis are conducted to assess the effectiveness of various AI-based pharmacy management approaches.

The remainder of the paper is organized as follows. Section 2 presents a detailed literature review of recent research on AI-based smart pharmacy systems. Section 3 provides a comparative analysis of existing approaches and highlights key research findings. Section 4 discusses the implications of these technologies for healthcare systems and identifies future research directions. Finally, Section 5 concludes the study by summarizing the major contributions and outlining potential advancements in AI-driven pharmacy inventory management.

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.

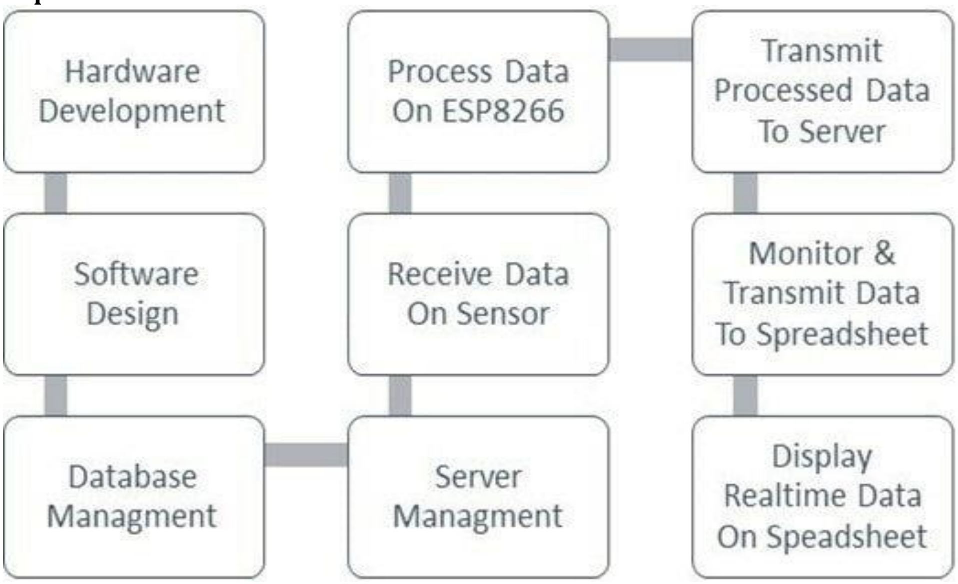
Chen et al. (2023) developed a hybrid deep learning model for pharmaceutical demand forecasting using heterogeneous datasets. The proposed system integrates multiple neural network architectures to analyze prescription data and supply chain records simultaneously. The authors concluded that hybrid deep 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	Key Contribution	Limitation
Patel	2020	Automated Inventory	Improved supply chain efficiency	Limited AI integration
Khan	2020	Smart Logistics	Demand forecasting optimization	High computational cost
Lee & Kumar	2021	RFID Tracking	Real-time drug tracking	Infrastructure cost
Mahmood	2021	AI Analytics	Reduced drug wastage	Limited scalability
Zhang	2022	Deep Learning	Accurate demand prediction	Data dependency
Al-Mutairi	2022	FEFO System	Expiry management	Limited automation
Abdulrahman	2023	IoT Supply Chain	Real-time monitoring	Security concerns
Chiu	2023	Smart Inventory AI	Efficient stock management	Integration complexity

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 analysis indicates that AI-driven inventory management systems significantly outperform traditional pharmacy inventory systems in terms of prediction accuracy, operational efficiency, and cost reduction. Studies consistently demonstrate that AI-based demand forecasting models reduce stock shortages and inventory costs while improving supply chain visibility. For instance, deep reinforcement learning techniques have been shown to reduce pharmaceutical inventory costs by approximately 30%.

IoT technologies further enhance these capabilities by providing real-time data for AI algorithms. Smart shelves equipped with sensors and RFID technology create a digital representation of pharmacy inventory, enabling automated stock monitoring and expiry tracking. The integration of AI and IoT technologies thus represents a significant advancement in pharmacy supply chain management.

However, several limitations remain across existing research studies. Many systems rely on centralized cloud infrastructures, which may introduce latency and security concerns. Additionally, the integration of heterogeneous datasets remains a significant technical challenge. These limitations highlight the need for more advanced hybrid AI architectures such as Siamese heterogeneous convolutional neural networks that can efficiently analyze complex pharmacy data environments.

Discussion

The integration of Artificial Intelligence (AI) and Internet of Things (IoT) technologies has revolutionized pharmacy inventory management systems by introducing intelligent automation and predictive analytics. Traditional pharmacy management systems often rely on manual monitoring and reactive decision-making processes, which can lead to inefficiencies such as medication shortages, excess stock, and wastage due to expired drugs. AI-driven smart pharmacy systems address these challenges by providing real-time monitoring, predictive demand forecasting, and automated inventory control.One of the most significant advantages of AI-based smart pharmacy systems is their ability to analyze large volumes of pharmaceutical data to identify hidden patterns and trends. Machine learning algorithms can process historical prescription records, patient medication usage patterns, seasonal disease trends, and supply chain logistics data to predict future drug demand. This predictive capability enables pharmacies to maintain optimal stock levels, ensuring the availability of essential medications while minimizing financial losses caused by overstocking or expired drugs.IoT technologies play a crucial role in enabling real-time data collection for these AI systems. Devices such as smart shelves, RFID tags, and environmental sensors continuously monitor pharmaceutical inventory and transmit data to centralized cloud platforms. These technologies create a dynamic digital representation of pharmacy inventory, allowing pharmacists to track medication availability and expiration dates with high accuracy. Studies have demonstrated that IoT-enabled smart shelf systems significantly reduce stock discrepancies and improve pharmacy operational efficiency. Deep learning architectures such as Siamese heterogeneous convolutional neural networks represent a promising advancement in pharmacy inventory optimization. These models are capable of comparing complex datasets and identifying similarities between historical demand patterns and current inventory trends. By learning relationships between heterogeneous datasets, SH-CNN architectures can generate more accurate demand forecasts and detect anomalies in pharmaceutical supply chains.

Despite these advantages, the implementation of AI-driven smart pharmacy systems also presents several challenges. Data privacy and security concerns are major issues because pharmacy systems contain sensitive patient information and prescription data. Ensuring secure data transmission and storage requires robust encryption mechanisms and regulatory compliance frameworks.Another challenge is the integration of diverse healthcare data sources, including electronic health records, prescription databases, IoT sensor networks, and supply chain systems. Achieving interoperability among these systems requires standardized data formats and communication protocols.

Furthermore, implementing IoT infrastructure and AI analytics platforms requires significant financial investment and technical expertise. Small pharmacies and healthcare facilities in developing regions may face difficulties adopting these technologies due to resource constraints.

Future research should focus on developing scalable AI architectures, integrating edge computing technologies, and improving interoperability among healthcare information systems. These advancements will enable the development of fully autonomous smart pharmacy ecosystems capable of optimizing pharmaceutical supply chains and improving healthcare delivery.

Conclusion

The integration of Artificial Intelligence (AI) and Internet of Things (IoT) technologies has significantly transformed pharmacy inventory management systems, enabling the development of intelligent smart pharmacy ecosystems capable of automated stock monitoring, predictive demand forecasting, and efficient supply chain management. This review paper examined recent advancements in AI-driven IoT-based smart pharmacy systems, with particular emphasis on the role of deep learning architectures such as Siamese heterogeneous convolutional neural networks in optimizing pharmaceutical inventory management.Traditional pharmacy inventory systems rely heavily on manual monitoring and static database management, which often result in inefficiencies such as medication shortages, overstocking, and wastage due to expired drugs. The increasing complexity of pharmaceutical supply chains and the growing demand for efficient healthcare services have highlighted the need for advanced technological solutions capable of addressing these challenges.AI-based predictive analytics models provide powerful tools for analyzing large volumes of pharmaceutical data, enabling pharmacies to forecast drug demand more accurately and optimize inventory levels. Machine learning techniques such as LSTM networks, reinforcement learning models, and convolutional neural networks have demonstrated significant improvements in demand forecasting accuracy compared with traditional statistical methods. These models can analyze historical prescription data, seasonal disease patterns, and patient medication usage trends to generate accurate predictions for future drug demand.IoT technologies further enhance the capabilities of AI-based pharmacy management systems by enabling real-time monitoring of pharmaceutical inventory. Smart shelves, RFID tracking systems, and sensor-enabled storage environments provide continuous updates on medication availability, expiration dates, and environmental conditions. These technologies create a dynamic digital representation of pharmacy inventory, enabling pharmacists to make data-driven decisions regarding stock replenishment and medication management.The integration of Siamese heterogeneous convolutional neural networks offers additional advantages by enabling the comparison of complex pharmacy datasets and identifying similarity relationships between historical and real-time demand patterns. This approach improves the accuracy of demand forecasting models and enhances the ability of pharmacy systems to detect anomalies and supply chain disruptions.

Despite the significant benefits of AI-driven smart pharmacy systems, several challenges remain in their widespread implementation. Data privacy and cybersecurity concerns must be addressed to protect sensitive patient information and ensure regulatory compliance. Additionally, the integration of heterogeneous healthcare data sources and IoT infrastructure requires standardized protocols and interoperable systems.Future research should focus on developing scalable AI architectures, integrating edge computing technologies, and improving interoperability between healthcare information systems. Hybrid AI models that combine deep learning, reinforcement learning, and predictive analytics may further enhance the performance of smart pharmacy systems. Furthermore, the adoption of blockchain technologies and secure data management frameworks may help address privacy and security challenges in healthcare data sharing.

In conclusion, AI-driven IoT smart pharmacy systems represent a transformative advancement in pharmaceutical supply chain management. By enabling predictive analytics, real-time monitoring, and automated decision-making, these technologies have the potential to significantly improve pharmacy efficiency, reduce medication wastage, and enhance patient care. Continued research and technological innovation will play a critical role in advancing the development of fully autonomous smart pharmacy ecosystems in the future.

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