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A Survey of Methods and Architectures for IoT-Based Smart Pharmacies for Optimizing Stock Management with Siamese Heterogeneous Convolutional Neural Networks

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Abstract

The integration of the Internet of Things (IoT) with artificial intelligence (AI) and deep learning has significantly transformed pharmaceutical inventory management systems. Traditional pharmacy stock management approaches often rely on manual processes and legacy systems, leading to inefficiencies such as inaccurate inventory tracking, drug shortages, overstocking, and medication wastage due to expiration. IoT-based smart pharmacy systems address these challenges by enabling real-time monitoring of inventory using connected devices such as sensors, RFID tags, and smart shelves. These systems generate continuous streams of data that can be analyzed using advanced machine learning and deep learning techniques.Recent advancements in deep learning, particularly convolutional neural networks (CNNs) and Siamese architectures, have shown promising results in analyzing complex pharmaceutical datasets. Siamese Heterogeneous Convolutional Neural Networks (SHCNNs) are especially effective in learning similarity relationships between historical and real-time inventory data, enabling accurate demand forecasting, anomaly detection, and intelligent stock classification. IoT-enabled systems combined with AI-driven analytics have demonstrated improvements in inventory accuracy, reduction in stockouts, and enhanced operational efficiency. This survey reviews methods and architectures used in IoT-based smart pharmacy systems, focusing on stock optimization strategies. It explores the integration of IoT with AI, blockchain, and edge computing technologies, highlighting their role in improving supply chain transparency and decision-making. The study also identifies challenges such as data security, interoperability, and implementation costs. The findings indicate that IoT-AI integrated systems significantly enhance pharmacy operations by enabling predictive analytics and automation. Future research directions include hybrid deep learning models, federated learning for secure data sharing, and edge-based architectures for real-time decision-making in smart healthcare environments.

Introduction

The rapid advancement of digital healthcare technologies has transformed pharmaceutical inventory management through the integration of the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and cloud computing. Pharmacy inventory management is essential for ensuring the continuous availability of medicines while minimizing operational costs, stock shortages, overstocking, and drug wastage. Traditional inventory systems rely on manual record-keeping and periodic stock verification, making them susceptible to human errors, delayed updates, and inefficient forecasting. These limitations negatively affect healthcare services and patient safety, creating a need for intelligent, automated inventory management systems capable of real-time monitoring and predictive decision-making.

IoT-based smart pharmacy systems address these challenges by enabling continuous monitoring of inventory using connected devices such as RFID tags, sensors, and smart shelves. These devices generate real-time data on stock levels, storage conditions, and product movement, providing healthcare organizations with improved visibility across pharmacy operations. The availability of continuous data streams enables timely stock replenishment, minimizes inventory inaccuracies, and supports efficient pharmaceutical supply chain management. Furthermore, IoT technologies facilitate seamless communication between healthcare stakeholders, improving operational efficiency and reducing medication shortages.

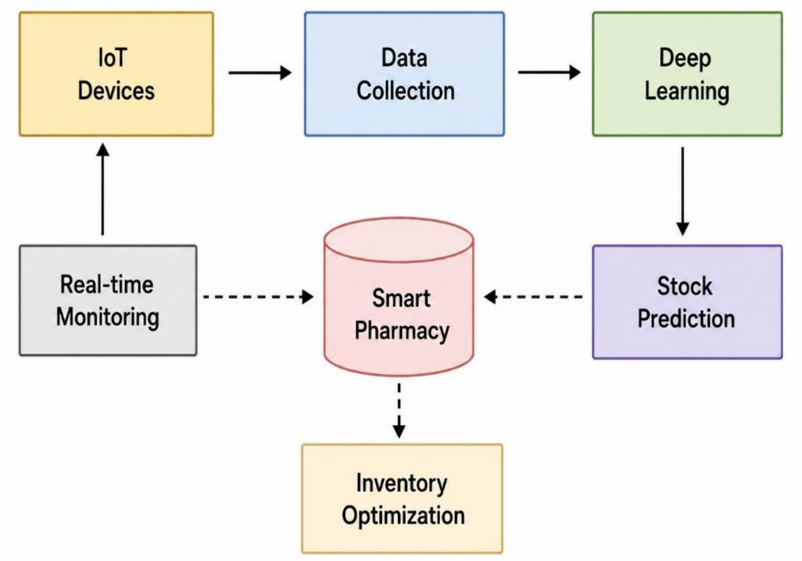

Figure 1. IoT-Enabled Inventory Management

Artificial intelligence and deep learning have further enhanced smart pharmacy systems by transforming large volumes of IoT-generated data into actionable insights. Deep learning architectures, particularly convolutional neural networks (CNNs), have demonstrated excellent performance in feature extraction and predictive analytics. More recently, Siamese Heterogeneous Convolutional Neural Networks (SHCNNs) have emerged as powerful models for learning similarity relationships between historical and real-time inventory data. These architectures improve demand forecasting, anomaly detection, stock classification, and inventory optimization by effectively processing heterogeneous pharmaceutical datasets. Their ability to identify complex patterns enables pharmacies to make proactive inventory decisions and reduce operational risks.

Recent research has also explored the integration of blockchain and edge computing with IoT-enabled pharmacy systems. Blockchain enhances supply chain transparency, traceability, and data integrity by securely recording pharmaceutical transactions, while edge computing enables real-time processing of IoT data with reduced latency. These complementary technologies improve responsiveness, security, and scalability in smart healthcare environments. This survey reviews recent methods and architectures for IoT-based smart pharmacies, emphasizing SHCNN-driven stock optimization and intelligent inventory management. It also discusses current challenges, including interoperability, data security, implementation costs, and computational complexity, while identifying future research directions involving hybrid deep learning models, federated learning, and edge-enabled intelligent healthcare systems.

Literature Review

The integration of Internet of Things (IoT), artificial intelligence (AI), and deep learning techniques has significantly transformed healthcare supply chains and pharmaceutical inventory management systems. Over the past few years (2020–2023), researchers have extensively explored intelligent systems for optimizing pharmacy stock management, reducing medication wastage, and improving supply chain transparency.

1. IoT-Based Smart Pharmacy Systems

The adoption of IoT technologies has been a key driver in the digital transformation of pharmacy systems. IoT enables real-time monitoring of inventory through interconnected devices such as RFID tags, sensors, and smart shelves. According to Tang et al. (2021), IoT-enabled healthcare supply chains improve visibility by continuously tracking drug movement and environmental conditions such as temperature and humidity. This is particularly important for temperature-sensitive pharmaceuticals like vaccines and biologics.

Lee and Lee (2020) highlighted that IoT systems provide seamless communication between devices and centralized platforms, allowing real-time data collection and analysis. In pharmacy environments, this translates into automated stock tracking and reduced dependence on manual inventory management. Furthermore, Mishra et al. (2022) emphasized that IoT-driven digital transformation improves coordination among supply chain stakeholders, including manufacturers, distributors, and pharmacies.

Recent studies have also explored the role of IoT in improving operational efficiency. Smart shelves equipped with sensors can automatically detect stock levels and update inventory databases. These systems significantly reduce discrepancies between physical and digital inventory records, thereby improving accuracy and reducing losses due to theft or mismanagement.

2. Artificial Intelligence in Pharmacy Inventory Management

Artificial intelligence has emerged as a powerful tool for enhancing decision-making in pharmacy systems. AI-based systems analyze large volumes of historical and real-time data to identify patterns and predict future demand. Nelson et al. (2020) discussed how AI is being used in pharmacy practice to improve medication management, optimize drug dispensing processes, and enhance clinical decision support. Chalasani et al. (2023) further demonstrated that AI-driven systems can automate routine pharmacy operations, reducing workload and improving efficiency. Machine learning algorithms such as regression models, decision trees, and support vector machines have been widely applied for demand forecasting and inventory optimization.

Bentivoglio et al. (2022) highlighted the effectiveness of machine learning models in supply chain demand forecasting. Their study showed that AI-based forecasting models outperform traditional statistical methods in terms of accuracy and adaptability. Similarly, Sharma et al. (2020) emphasized that machine learning techniques can identify hidden patterns in supply chain data, enabling better planning and resource allocation.

AI systems also play a critical role in predictive analytics. By analyzing historical consumption patterns and external factors such as seasonal trends and disease outbreaks, AI models can forecast medication demand with high accuracy. This capability is essential for preventing stockouts and ensuring the availability of essential drugs.

3. Deep Learning Approaches for Inventory Optimization

Deep learning, a subset of machine learning, has gained significant attention in recent years due to its ability to process large and complex datasets. Alzubaidi et al. (2021) provided a comprehensive review of deep learning architectures, highlighting the effectiveness of convolutional neural networks (CNNs) in feature extraction and pattern recognition.

In the context of pharmacy inventory management, deep learning models have been used for demand forecasting, anomaly detection, and stock classification. Chen et al. (2022) proposed a knowledge graph-enhanced deep learning model for pharmaceutical demand forecasting, demonstrating improved accuracy compared to traditional models.

Reinforcement learning, another advanced AI technique, has also been applied to inventory optimization. Ahmadi et al. (2022) developed intelligent inventory management models using reinforcement learning algorithms, which dynamically adjust inventory policies based on changing demand patterns. These models minimize costs while ensuring adequate stock levels.

Temizöz et al. (2020) further explored the use of deep reinforcement learning for inventory control, showing that such models can learn optimal stocking policies through continuous interaction with the environment. These approaches are particularly useful in dynamic healthcare environments where demand patterns are unpredictable.

4. Siamese Neural Networks and SHCNN Architectures

Siamese neural networks have emerged as a promising deep learning architecture for applications involving similarity learning. These networks consist of two identical subnetworks that share parameters and learn relationships between input pairs. In pharmacy systems, Siamese networks can compare historical demand data with real-time inventory data to identify anomalies and predict shortages.

Although research specifically focusing on Siamese Heterogeneous Convolutional Neural Networks (SHCNNs) in pharmacy systems is still emerging, related studies in deep learning indicate their potential for handling heterogeneous datasets. SHCNN models combine multiple feature extraction techniques, enabling them to process complex data from IoT devices, sales records, and supply chain systems simultaneously.

Zhang and Tao (2020) introduced the concept of Artificial Intelligence of Things (AIoT), which integrates IoT with AI models for intelligent decision-making. This concept provides a foundation for developing SHCNN-based smart pharmacy systems, where IoT-generated data is analyzed using advanced neural network architectures.

Zogaan et al. (2023) demonstrated the effectiveness of deep learning models in healthcare supply chain risk prediction, highlighting their ability to identify disruptions and optimize supply chain performance. These findings suggest that SHCNN architectures could further enhance predictive capabilities in pharmacy systems.

5. Blockchain Integration in Smart Pharmacy Systems

Blockchain technology has been increasingly integrated with IoT and AI systems to improve transparency and security in pharmaceutical supply chains. Kamble et al. (2020) discussed how blockchain enables traceability and ensures data integrity by providing tamper-proof transaction records.

Kumar et al. (2020) emphasized that blockchain can address challenges related to counterfeit drugs by ensuring the authenticity of pharmaceutical products. When combined with IoT tracking devices, blockchain systems provide end-to-end visibility in the supply chain.

The integration of blockchain with AI and IoT creates a secure and transparent ecosystem for pharmaceutical inventory management. This combination enhances trust among stakeholders and improves regulatory compliance.

6. Digital Transformation and Smart Supply Chains

Digital transformation has played a crucial role in improving the efficiency of pharmaceutical supply chains. Mishra et al. (2022) highlighted that digital technologies such as IoT, AI, and cloud computing enable better coordination and communication among supply chain participants.

Long et al. (2023) proposed AI-based models for selecting optimal healthcare supply chain structures, demonstrating the potential of intelligent systems in improving supply chain performance. These models consider multiple factors such as cost, efficiency, and sustainability.

Yin et al. (2020) discussed the role of IoT in smart manufacturing systems, which can be extended to pharmaceutical production and distribution. These systems enable real-time monitoring and control of production processes, ensuring consistent quality and efficient resource utilization.

7. Challenges in IoT-Based Smart Pharmacy Systems

Despite significant advancements, several challenges remain in the implementation of IoT-based smart pharmacy systems. One of the major concerns is data security and privacy. Healthcare systems handle sensitive patient and inventory data, making them vulnerable to cyber threats.

Interoperability is another challenge, as different healthcare systems often use incompatible technologies and standards. This makes it difficult to integrate IoT devices, AI models, and existing healthcare infrastructure.

High implementation costs also pose a barrier to adoption, particularly for small and medium-sized healthcare facilities. The deployment of IoT devices, cloud infrastructure, and AI systems requires significant investment.

Additionally, there is a need for skilled personnel capable of managing and maintaining advanced digital systems. Training healthcare professionals to use these technologies effectively is essential for successful implementation.

8. Research Gaps and Future Directions

Although significant progress has been made in IoT-based smart pharmacy systems, several research gaps remain. Most existing studies focus on individual technologies rather than integrated systems combining IoT, AI, and blockchain.

There is also limited research on the application of advanced deep learning architectures such as SHCNNs in pharmacy inventory management. Future research should focus on developing hybrid models that combine multiple AI techniques to improve prediction accuracy.

Edge computing is another promising area for future research. By processing data closer to IoT devices, edge computing can reduce latency and enable real-time decision-making in pharmacy systems.

Federated learning is also gaining attention as a privacy-preserving machine learning technique. This approach allows multiple healthcare institutions to collaborate on model training without sharing sensitive data.

Comparative Table

Study	Year	Technology Used	Method/Model	Dataset Type	Key Contribution	Advantages	Limitations
Ahmadi et al.	2022	AI + Reinforcement Learning	Q-learning, Policy Optimization	Pharmaceutical inventory datasets	Dynamic inventory optimization using RL	Adaptive decision-making, cost reduction, minimizes stockouts	Requires large training data, complex implementation
Chalasani et al.	2023	Artificial Intelligence	Machine Learning Models (SVM, Regression, Decision Trees)	Pharmacy operational data	AI-based decision support in pharmacy systems	Improves operational efficiency, reduces manual workload	Limited handling of complex and heterogeneous data
Tang et al.	2021	IoT	Sensor-based Monitoring	Real-time IoT data (RFID, sensors)	Real-time tracking of pharmaceutical inventory	High accuracy, automation, continuous monitoring	Network dependency, security vulnerabilities
Mishra et al.	2022	IoT + Digital Transformation	IoT-enabled supply chain framework	Supply chain data	Improved coordination across stakeholders	Enhances visibility and collaboration	High implementation cost
Bentivoglio et al.	2022	AI + ML	Demand Forecasting Models	Historical sales data	Accurate demand prediction using ML	Low computational cost, interpretable models	Less accurate than deep learning for complex data
Chen et al.	2022	Deep Learning	Knowledge Graph + Neural Networks	Pharmaceutical demand datasets	Improved forecasting accuracy using deep learning	High accuracy, handles complex patterns	Requires large datasets and high computation
Temizöz et al.	2020	Reinforcement Learning	Deep Q-Network (DQN)	Inventory control simulations	Adaptive inventory policies	Dynamic learning capability	Training complexity and instability
Alzubaidi et al.	2021	Deep Learning	CNN Architectures	Large-scale healthcare datasets	Feature extraction and pattern recognition	High accuracy, automatic feature learning	High computational cost
Kamble et al.	2020	Blockchain + IoT	Distributed Ledger Technology	Supply chain transaction data	Secure and transparent drug tracking	Data integrity, tamper-proof system	Scalability issues, energy consumption
Kumar et al.	2020	Blockchain	Smart contracts, traceability systems	Pharmaceutical logistics data	Prevention of counterfeit drugs	High security and trust	Integration complexity

Zhang & Tao	2020	AIoT (AI + IoT)	Integrated intelligent systems	IoT-generated data streams	Intelligent decision-making using AIoT	Combines real-time data + intelligence	Complex system architecture
Zogaan et al.	2023	Deep Learning	Predictive Neural Networks	Healthcare supply chain data	Risk prediction in supply chains	Early disruption detection	Limited real-world deployment
Smart Shelves Study	2022	IoT + RFID	Automated stock monitoring	Real-time shelf data	Automated inventory updates	Reduces manual errors	Hardware cost
AI Forecasting Study	2023	AI + ML	Predictive analytics models	Historical + real-time data	Demand prediction and planning	Improves forecasting accuracy	Depends on data quality

Comparative Analysis

The comparative analysis of recent studies demonstrates a clear transition from conventional pharmacy inventory management to intelligent, IoT-enabled smart pharmacy systems. Traditional inventory approaches, based on manual record-keeping and periodic stock verification, often suffer from inaccurate inventory tracking, delayed updates, stock shortages, overstocking, and medication wastage. In contrast, IoT technologies provide continuous monitoring through RFID tags, sensors, and smart shelves, enabling real-time visibility of pharmaceutical inventory. This automation improves data accuracy, reduces human intervention, and supports timely stock replenishment. Nevertheless, IoT-based systems also introduce challenges related to cybersecurity, infrastructure costs, interoperability, and network dependency, which remain significant barriers to widespread implementation.

Artificial intelligence and deep learning have substantially improved inventory forecasting and decision-making in smart pharmacy systems. Machine learning techniques offer reliable forecasting with relatively low computational requirements, whereas deep learning architectures, particularly convolutional neural networks (CNNs), provide superior performance by automatically extracting complex features from heterogeneous pharmaceutical datasets. Siamese Heterogeneous Convolutional Neural Networks (SHCNNs) represent a significant advancement by learning similarity relationships between historical and real-time inventory data. This capability enables accurate demand forecasting, anomaly detection, stock classification, and early identification of supply chain disruptions. However, these models require large training datasets, extensive computational resources, and optimized parameter configurations, limiting their practical deployment in resource-constrained healthcare environments.

The literature also highlights the growing importance of complementary technologies such as blockchain, reinforcement learning, and edge computing in enhancing smart pharmacy operations. Blockchain strengthens pharmaceutical supply chains by ensuring secure, transparent, and tamper-resistant tracking of medicines, reducing counterfeit drugs and improving regulatory compliance. Reinforcement learning enables adaptive inventory optimization through continuous interaction with dynamic demand environments, while edge computing processes IoT data closer to the source, reducing latency and supporting real-time decision-making. Although these technologies significantly improve operational efficiency, their implementation is often constrained by scalability issues, computational complexity, integration challenges, and deployment costs.

Overall, the comparative evaluation indicates that integrated IoT-AI systems outperform standalone technologies by combining real-time data acquisition with intelligent analytics and automated decision-making. The convergence of IoT, SHCNNs, blockchain, edge computing, and reinforcement learning provides a comprehensive framework for optimizing pharmaceutical inventory management, improving stock accuracy, reducing wastage, and enhancing patient care. Despite these advances, challenges related to data privacy, interoperability, standardized datasets, computational efficiency, and explainable AI remain unresolved. Future research should focus on developing scalable, secure, and cost-effective hybrid architectures incorporating federated learning, edge intelligence, and advanced deep learning models to support next-generation smart pharmacy systems.

Discussion

The integration of IoT and AI technologies has revolutionized pharmacy inventory management systems by enabling real-time monitoring and predictive analytics. Traditional inventory systems often suffer from inefficiencies such as delayed updates, inaccurate records, and lack of predictive capabilities. IoT-based systems address these challenges by providing continuous monitoring of inventory levels through connected devices.

AI and deep learning models further enhance these systems by analyzing large datasets and providing actionable insights. Siamese neural networks enable similarity-based analysis, which is particularly useful for anomaly detection and demand forecasting. These models improve decision-making accuracy and reduce the risk of stockouts.

However, challenges such as data privacy, system integration, and implementation costs must be addressed to ensure widespread adoption. Future research should focus on developing scalable and secure architectures for smart pharmacy systems.

Conclusion

IoT-based smart pharmacy systems represent a significant advancement in healthcare technology, offering improved efficiency, accuracy, and reliability in inventory management. The integration of IoT devices with AI and deep learning models enables real-time monitoring, predictive analytics, and automated decision-making. Siamese Heterogeneous Convolutional Neural Networks provide a powerful approach for analyzing complex pharmaceutical datasets and improving demand forecasting accuracy. These models enable pharmacies to optimize stock levels, reduce wastage, and enhance patient safety.

Despite these advancements, challenges such as data security, interoperability, and implementation costs remain. Addressing these challenges will be essential for the successful deployment of smart pharmacy systems. Future research should focus on hybrid AI models, edge computing, and blockchain integration to further enhance the capabilities of smart pharmacy systems.

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