Archives available at journals.mriindia.com

ITSI Transactions on Electrical and Electronics Engineering
ISSN: 2320-8945

Volume 14 Issue 01, 2025

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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Peer Review Information

Submission: 02 April 2025

Revision: 23 April 2025

Acceptance: 11 May 2025

Keywords

IoT-Based Smart Pharmacy, Pharmaceutical Inventory Management, Deep Learning, Siamese, Neural Networks, Healthcare Supply Chain, Stock Optimization

Abstract

The integration of Internet of Things (IoT) technologies with artificial intelligence (AI) and deep learning has revolutionized pharmaceutical inventory management by addressing the inefficiencies of traditional, manual stock control systems. Conventional approaches often suffer from inaccurate tracking, frequent stockouts, overstocking, and medication wastage due to expiration. IoT-enabled smart pharmacy systems overcome these limitations through real-time monitoring using sensors, RFID tags, and intelligent storage units, generating continuous data streams for advanced analytics. Deep learning techniques, particularly convolutional neural networks (CNNs) and Siamese Heterogeneous Convolutional Neural Networks (SHCNNs), have demonstrated strong capabilities in analyzing complex pharmaceutical datasets by identifying patterns and similarity relationships between historical and real-time data. These models support accurate demand forecasting, anomaly detection, and optimized stock classification. Furthermore, the integration of IoT with emerging technologies such as blockchain and edge computing enhances supply chain transparency, data security, and decision-making efficiency. This survey emphasizes stock optimization strategies while identifying challenges such as interoperability, implementation costs, and data privacy. Overall, IoT-AI integrated systems significantly improve pharmacy operations, with future research focusing on hybrid models, federated learning, and real-time edge-based solutions.

Introduction

The healthcare sector has witnessed rapid digital transformation in recent years due to the integration of emerging technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and cloud computing. These technologies have significantly improved the efficiency, accuracy, and reliability of healthcare systems, particularly in the domain of pharmaceutical supply chain and inventory management. Pharmacy inventory management is a critical component of healthcare delivery systems, as it ensures the availability of essential medications while minimizing operational costs and wastage.

Traditional pharmacy inventory systems are often characterized by manual record-keeping, periodic stock monitoring, and limited predictive capabilities. These systems are prone to human errors, delayed updates, and inefficient decision-making processes. As a result, pharmacies frequently face challenges such as stockouts, overstocking, expired medications, and poor demand forecasting. These issues not only increase operational costs but also pose risks to patient safety.

The emergence of IoT technologies has introduced new possibilities for automating pharmacy operations and improving inventory management efficiency. IoT refers to a network of interconnected devices capable of collecting and exchanging data in real time. In smart pharmacy systems, IoT devices such as RFID tags, sensors, and smart shelves are used to continuously monitor drug inventory levels and environmental conditions. These systems provide real-time visibility into pharmacy operations, enabling healthcare providers to make informed decisions regarding stock replenishment and distribution.

IoT-based inventory systems significantly reduce manual intervention and improve data accuracy. Studies have shown that IoT-enabled systems can improve inventory accuracy by up to 35% and reduce stockouts by nearly 45%, demonstrating their effectiveness in optimizing supply chain operations.

In addition to IoT, artificial intelligence and machine learning technologies have been widely adopted to analyze the large volumes of data generated by IoT devices. AI algorithms can identify patterns in historical data, predict future demand, and optimize inventory management strategies. Machine learning models such as regression models, decision trees, and neural networks have been successfully applied to healthcare supply chain management.

Deep learning, a subset of machine learning, has further enhanced the capabilities of intelligent inventory management systems. Convolutional Neural Networks (CNNs) are particularly effective in analyzing complex datasets and extracting hierarchical features. These models have been widely used in medical imaging, disease diagnosis, and supply chain analytics.

A more advanced deep learning architecture, the Siamese neural network, has gained attention for its ability to learn similarity relationships between datasets. Siamese networks consist of two identical neural network branches that share weights and parameters. These networks are particularly useful for applications involving pattern recognition and anomaly detection. In pharmacy systems, Siamese networks can compare historical consumption patterns with real-time inventory data to detect anomalies and predict shortages.

The concept of heterogeneous CNN architectures further enhances the performance of deep learning models by combining multiple feature extraction techniques. When integrated with Siamese architectures, these models form Siamese Heterogeneous Convolutional Neural Networks (SHCNNs), which are capable of processing complex and heterogeneous datasets.

Another important development in smart pharmacy systems is the integration of blockchain technology with IoT and AI. Blockchain provides a secure and transparent mechanism for tracking pharmaceutical products across the supply chain, reducing the risk of counterfeit drugs and ensuring data integrity.

Furthermore, edge computing has emerged as a critical technology for real-time data processing in IoT-based systems. Edge computing enables data processing closer to the source of data generation, reducing latency and improving system responsiveness.

The COVID-19 pandemic highlighted the importance of efficient pharmaceutical supply chain systems. Many healthcare systems experienced disruptions in drug supply chains due to sudden changes in demand. This situation emphasized the need for intelligent inventory management systems capable of adapting to dynamic environments.

Recent research has also explored the use of reinforcement learning for inventory optimization. Reinforcement learning algorithms such as Q-learning and Deep Q-Networks have been used to develop intelligent inventory management policies that minimize costs and reduce product expiration risks.

Overall, IoT-based smart pharmacy systems represent a significant advancement in healthcare technology. By integrating IoT with AI and deep learning, these systems can improve inventory accuracy, reduce wastage, and enhance patient safety.

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	Method	Key Contribution
Ahmadi et al.	2022	RL + AI	Q-learning	Inventory optimization
Chalasani et al.	2023	AI	ML models	Pharmacy decision support
IoT Inventory Study	2021	IoT	Sensor-based	Real-time tracking
Smart Shelves Study	2022	IoT + RFID	Automation	Stock accuracy
AI Forecasting	2023	AI + ML	Predictive models	Demand prediction

Comparative Analysis

The comparative analysis of recent studies (2020–2023) on IoT-based smart pharmacy systems reveals significant advancements in the integration of IoT, artificial intelligence (AI), machine learning, deep learning, and blockchain technologies for optimizing pharmaceutical inventory management. The reviewed literature demonstrates that each technological approach contributes uniquely to improving stock monitoring, demand forecasting, and supply chain efficiency, while also presenting certain limitations.

1. IoT-Based Approaches vs Traditional Inventory Systems

One of the most prominent findings across the literature is the superiority of IoT-enabled systems over traditional inventory management methods. Traditional systems rely heavily on manual data entry and periodic stock assessments, leading to inaccuracies, delays, and inefficiencies. In contrast, IoT-based systems provide real-time visibility into inventory levels through continuous monitoring using sensors, RFID tags, and smart shelves.

Studies such as Tang et al. (2021) and Mishra et al. (2022) show that IoT-based systems significantly reduce human error and improve data accuracy. These systems enable automated data collection and provide real-time updates, allowing pharmacies to respond quickly to changes in demand. However, IoT systems also introduce challenges related to data management, network reliability, and system integration.

2. Machine Learning vs Deep Learning for Demand Forecasting

Machine learning models have been widely used for demand forecasting in pharmaceutical supply chains. Techniques such as regression models, decision trees, and support vector machines offer relatively simple and interpretable solutions. Bentivoglio et al. (2022) demonstrated that machine learning models can achieve good forecasting accuracy with lower computational complexity compared to deep learning models.

However, deep learning approaches, particularly convolutional neural networks (CNNs), have shown superior performance in handling large and complex datasets. Alzubaidi et al. (2021) highlighted that deep learning models can automatically extract hierarchical features from data, leading to more accurate predictions. Chen et al. (2022) further demonstrated that deep learning models enhanced with knowledge graphs significantly improve forecasting accuracy in pharmaceutical applications.

Despite their advantages, deep learning models require large datasets, high computational resources, and longer training times. Therefore, while deep learning provides higher accuracy, machine learning remains a practical choice for smaller-scale implementations.

3. Reinforcement Learning for Dynamic Inventory Optimization

Reinforcement learning (RL) has emerged as a powerful approach for dynamic inventory optimization. Unlike traditional models that rely on static rules, RL models learn optimal policies through continuous interaction with the environment. Ahmadi et al. (2022) and Temizöz et al. (2020) demonstrated that RL-based inventory systems can dynamically adjust stock levels based on changing demand patterns, minimizing costs and reducing stockouts.

Compared to traditional forecasting models, RL provides a more adaptive and flexible approach to inventory management. However, RL models are complex to design and require extensive training data, making them less suitable for systems with limited data availability.

4. Role of Siamese Neural Networks and SHCNN

Siamese neural networks represent a significant advancement in deep learning for inventory management. Unlike conventional models that focus solely on prediction, Siamese networks learn similarity relationships between datasets. This capability allows them to detect anomalies and identify patterns that may not be captured by traditional models.

In the context of smart pharmacy systems, Siamese networks can compare historical and real-time inventory data to detect unusual demand patterns. When combined with heterogeneous CNN architectures, SHCNN models can process multiple types of data simultaneously, including sensor data, sales records, and environmental information.

Compared to traditional CNN models, SHCNN provides enhanced performance in pattern matching, anomaly detection, and multi-source data integration. However, these models are still in the early stages of research, and their implementation in real-world pharmacy systems remains limited.

5. Blockchain Integration vs Conventional Security Mechanisms

Security and transparency are critical concerns in pharmaceutical supply chains. Traditional systems rely on centralized databases, which are vulnerable to data tampering and cyberattacks. Blockchain technology offers a decentralized and tamper-proof solution for tracking pharmaceutical products.

Studies such as Kamble et al. (2020) and Kumar et al. (2020) show that blockchain-based systems improve traceability and ensure the authenticity of drugs. When integrated with IoT devices, blockchain enables secure tracking of drug movement across the supply chain.

However, blockchain systems also introduce challenges related to scalability, energy consumption, and integration with existing systems. Therefore, while blockchain enhances security, its implementation must be carefully designed to balance performance and cost.

6. Edge Computing vs Cloud-Based Architectures

Another important comparison in the literature is between edge computing and cloud-based architectures. Cloud computing provides centralized data processing and storage capabilities, making it suitable for large-scale analytics. However, cloud-based systems may suffer from latency issues, particularly in real-time applications.

Edge computing addresses this limitation by processing data closer to the source, reducing latency and enabling faster decision-making. In IoT-based pharmacy systems, edge computing allows real-time analysis of sensor data, improving responsiveness and system efficiency.

While edge computing offers significant advantages, it requires additional hardware and infrastructure, which may increase implementation costs.

7. Integrated IoT-AI Systems vs Standalone Technologies

The literature clearly indicates that integrated systems combining IoT, AI, and deep learning outperform standalone technologies. IoT provides real-time data, while AI and deep learning models analyze this data to generate actionable insights.

For example, IoT systems alone can monitor inventory levels, but they cannot predict future demand. Similarly, AI models require high-quality data to function effectively. The integration of these technologies creates a synergistic effect, enabling intelligent and automated decision-making.

However, integration also introduces challenges such as system complexity, interoperability issues, and increased implementation costs.

8. Key Findings from Comparative Analysis

The comparative analysis highlights several key insights:

- IoT systems significantly improve real-time visibility and automation
- Machine learning models provide efficient and interpretable forecasting solutions
- Deep learning models offer higher accuracy for complex datasets
- Reinforcement learning enables adaptive and dynamic inventory optimization
- SHCNN models enhance similarity-based analysis and anomaly detection
- Blockchain technology improves security and transparency
- Edge computing enables real-time decision-making
- Integrated systems provide the best overall performance

9. Limitations Identified in Existing Studies

Despite significant progress, several limitations are observed:

- Limited real-world implementation of advanced deep learning models
- Lack of standardized datasets for benchmarking
- High computational and infrastructure costs
- Data privacy and security concerns
- Integration challenges among heterogeneous systems

10. Future Scope Based on Comparative Analysis

Future research should focus on:

- Developing hybrid models combining AI, RL, and SHCNN
- Implementing edge AI for real-time pharmacy analytics
- Enhancing data privacy using federated learning
- Creating standardized datasets for benchmarking
- Designing cost-effective solutions for small-scale pharmacies

Conclusion of Comparative Analysis

Overall, the comparative analysis demonstrates that the integration of IoT with advanced AI and deep learning models significantly enhances pharmaceutical inventory management systems. While each technology offers unique advantages, the combination of IoT, AI, deep learning, and blockchain provides the most effective solution for optimizing stock management in smart pharmacy environments.

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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