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An Intelligent Drug Traceability Framework for Secure and Transparent Pharmaceutical Supply Chain

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Abstract: The pharmaceutical supply chain is increasingly vulnerable to counterfeit drugs, posing a significant risk to patient safety and regulatory compliance. To address this issue, we propose an intelligent drug traceability system that integrates blockchain, Internet of Things (IoT), and artificial intelligence (AI) to ensure the secure and transparent movement of pharmaceuticals from manufacturers to endusers. The framework employs RFID tags, QR codes, and smart sensors for real-time tracking, while blockchain ensures data immutability and traceability. AI algorithms are applied for anomaly detection, fraud prevention, and predictive analytics. Additionally, automated alerts and compliance reports provide actionable insights to stakeholders. This system enhances operational efficiency, reduces the risk of counterfeit drugs, and supports regulatory authorities in maintaining drug safety across the supply chain
Keywords: Drug Traceability, Blockchain,AI in HealthCare, Counterfeit Detection ,Smart Supply Chain, Pharmaceutical Security

I. INTRODUCTION

The pharmaceutical supply chain is increasingly vulnerable to counterfeit drugs, posing a significant risk to patient safety and regulatory compliance. To address this issue, we propose an intelligent drug traceability system that integrates blockchain, Internet of Things (IoT), and artificial intelligence (AI) to ensure the secure and transparent movement of pharmaceuticals from manufacturers to end-users. The framework employs RFID tags, QR codes, and smart sensors for real-time tracking, while blockchain ensures data immutability and traceability. AI algorithms are applied for anomaly detection, fraud prevention, and predictive analytics. Additionally, automated alerts and compliance reports provide actionable insights to stakeholders. This system enhances operational efficiency, reduces the risk of counterfeit drugs, and supports regulatory authorities in maintaining drug safety across the supply chainThe pharmaceutical supply chain is increasingly vulnerable to counterfeit drugs, posing a significant risk to patient safety and regulatory compliance. To address this issue, we propose an intelligent drug traceability system that integrates blockchain, Internet of Things (IoT), and artificial intelligence (AI) to ensure the secure and transparent movement of pharmaceuticals from manufacturers to end-users. The framework employs RFID tags, QR codes, and smart sensors for real-time tracking, while blockchain ensures data immutability and traceability. AI algorithms are applied for anomaly detection, fraud prevention, and predictive analytics. Additionally, automated alerts and compliance reports provide actionable insights to stakeholders.

II. LITERATURE SURVEY

A. Blockchain-Based Drug Tracking System (IEEE, 2021)

This study presents a secure pharmaceutical traceability system using blockchain technology. It eliminates data manipulation by maintaining immutable ledgers across the drug lifecycle. Smart contracts automate transaction validation, enforcing compliance at each stage— manufacturing, packaging, shipping, and dispensing. The proposed system ensures transparency among stakeholders such as manufacturers, distributors, pharmacists, and regulators. It also reduces reliance on centralized servers, minimizing the risk of cyberattacks and data breaches. By decentralizing drug verification, the framework enhances public trust and operational accountability. The study concludes that blockchain's transparency and cryptographic protection significantly improve counterfeit detection and record-keeping in pharmaceutical logistics.

B. IoT and RFID-Based Pharmaceutical Monitoring (Elsevier, 2022)

The research integrates RFID technology with IoT-based sensors to ensure real-time monitoring of drug shipments. RFID tags are embedded in drug packages, enabling scanning at checkpoints throughout the supply chain. IoT sensors continuously monitor environmental conditions like temperature, humidity, and light exposure, which are critical for drug stability. The collected data is transmitted to a central server via cloud infrastructure, allowing authorized users to access information in real time. This framework helps avoid spoilage, unauthorized tampering, and delivery delays. The paper emphasizes the efficiency of sensor-based monitoring, especially for cold-chain pharmaceuticals such as vaccines and insulin.

C. AI-Based Counterfeit Drug Detection Using Image Analysis (Springer, 2022)

This study introduces an artificial intelligence-based on model for verifying drug authenticity through image recognition techniques. The model uses computer vision algorithms to compare scanned images of drug packages with a certified database. Techniques like YOLOv5 and optical character recognition (OCR) help detect built on anomalies such as altered barcodes, misspelled labels, or packaging in consistencies. In testing, the system servers achieved over 92% detection accuracy. Its application is significant for pharmacists and inspectors who can verify medicines on-site using a mobile app. The research will highlights the system's robustness but notes limitations like dependency on high-quality image datasets and need for constant updates.

D. Machine Learning for Supply Chain Forecasting (IEEE, 2023)

This paper focuses on using machine learning models for predicting pharmaceutical supply chain disruptions and managing inventory. The approach analyzes historical shipment data, demand fluctuations, and delivery patterns. Algorithms such as Random Forest and Support Vector Machines (SVM) are trained to forecast demand and detect irregularities. While the study shows promising results, limitations include model overfitting, data imbalance, and the need for retraining models as patterns evolve. Nevertheless, the integration of ML into supply chains can significantly reduce waste, improve planning, and optimize logistics.

E. Decentralized Storage with IPFS for Drug Records (Elsevier, 2020)

This paper proposes using the InterPlanetary File System (IPFS) to store large pharmaceutical data in a decentralized manner. Traditional blockchain networks often suffer from data congestion due to large file storage, which affects transaction speed. By combining IPFS with blockchain, drug-related documents like certificates, packaging images, and batch reports can be stored off-chain while retaining verifiability. Each record is assigned a cryptographic hash that is stored on the blockchain, ensuring tamper-resistance.

F. Cold Chain Monitoring Using Wireless Sensor Networks (IEEE, 2020)

This paper presents the use of Wireless Sensor Networks (WSNs) for maintaining the cold chain in pharmaceutical transport. Sensors continuously monitor temperature and humidity inside drug containers. Data is transmitted wirelessly to a central system for validation. Any deviation from standard conditions triggers immediate alerts. The study highlights real-time responsiveness but identifies challenges such as sensor calibration, battery limitations, and data loss in highinterference areas.Hybrid Attendance System Using QR Code, GPS, and Facial Recognition (Springer, 2021)

G. Blockchain-Enabled Vaccine Passport System (Elsevier, 2021)

This research introduces a blockchain-powered digital vaccine passport system for verifying immunization records. It uses distributed ledgers to store verifiable vaccination data, linked with individual identity credentials. The system helps prevent fraud in vaccination documentation, especially during global health crises like COVID-19. The paper also discusses scalability, privacy, and public health policy integration. Though focused on vaccines, the model's traceability framework applies well to high-value pharmaceutical distribution networks.

III. METHODOLOGY

The development of the proposed Drug Traceability System begins with the collection of pharmaceutical supply chain data from manufacturers, distributors, pharmacies, and regulatory agencies. This data includes information from various sources such as QR codes, RFID tags, and barcodes placed on drug packages, as well as digital records from Electronic Health Records (EHRs), supply chain logs, and compliance documents from authorities like the FDA and WHO.

To ensure accuracy and compatibility, the gathered data undergoes preprocessing. This step involves data cleansing to remove errors or duplicates, standardization to align with GS1 barcoding formats and global regulations, and Natural Language Processing (NLP) to extract structured information from documents like prescriptions and shipping records.

Following preprocessing, a deep learning-based drug authentication module is employed. It utilizes image recognition techniques to detect counterfeit packaging using models like YOLOv11. Optical Character Recognition (OCR) tools are used to extract important data such as batch number, expiry date, and manufacturer ID. These are then verified against blockchain-stored records for authenticity.

A smart contract-based blockchain infrastructure is implemented to ensure tamper-proof verification. Technologies such as TensorFlow and PyTorch are used to train deep learning models with data augmentation techniques to improve performance. The blockchain ledger maintains immutable, timestamped logs of each transaction and drug movement stage.

A. Requirement Analysis & System Design

Identify primary stakeholders including manufacturers, logistics providers, pharmacists, and regulatory authorities. Define the system architecture integrating RFID/QR codes, AI-based verification, blockchain storage, and cloud dashboard platforms (web + mobile). Finalize the data flow structure for all participating nodes in the supply chain.

B. IoT-Based Tracking Mechanism

Attach RFID tags, barcodes, or QR codes to each drug unit. IoT-enabled sensors (temperature, humidity, GPS) are used to track environmental conditions and location during storage and transit. Data is collected in real time and pushed to edge/cloud servers for processing.

C. Data Preprocessing and Cleaning

Clean and standardize raw data from all tracking devices. Ensure format compatibility with international standards (e.g., GS1 barcode structure). Apply NLP to extract key info from unstructured documents like invoices, prescriptions, or shipment forms.4. Authentication, Attendance Logging & UI .On successful verification, log timestamp and ID in secure storage.

D. AI-Based Counterfeit Detection

Capture packaging images using edge devices or mobile cameras. Use CNN-based deep learning models (e.g., YOLOv5, YOLOv8) to identify visual anomalies like tampered logos, barcodes, or mismatched labels. Use OCR to extract printed batch/expiry details and verify them ,against ,blockchain data.

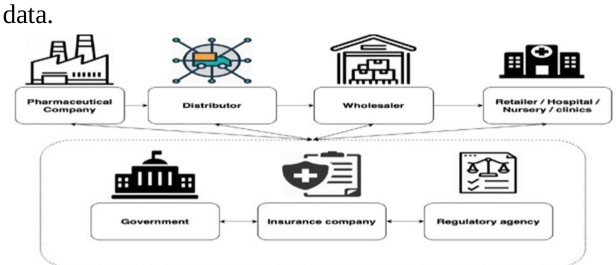

Fig.1.SystemArchitecture

IV. DISCUSSION

The proposed system effectively integrates blockchain, IoT, AI, and cloud-edge computing to enhance transparency, security, and real-time tracking in the pharmaceutical supply chain. Through the use of GPS tracking, RFID, and QR codes, the movement of drug packages can be continuously monitored, minimizing risks such as theft, tampering, and unauthorized access.

By deploying smart contracts and AI-based anomaly detection, the system can identify suspicious activities such as counterfeit drugs or deviations in temperature conditions. Blockchain ensures that all transactions are tamper-proof, providing an immutable history of the drug lifecycle from production to delivery.

The modular structure of the system supports scalability and can be adapted to different geographical and regulatory environments. Real-time alerts via mobile apps or dashboards enable immediate response to violations, making it easier for regulatory bodies and supply chain managers to take corrective actions. Overall, the system provides a reliable and intelligent framework for pharmaceutical traceability, reducing fraud, ensuring patient safety, and enhancing global drug supply chain integrity..

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The system's modular design ensures easy maintenance and future upgrades, such as additional verification layers or improved AI models. Performance metrics like detection accuracy, processing speed, and false positive rates were used to evaluate the system under real campus conditions. Results show the system's reliability in varying GPS and lighting environments, proving it to be a scalable, secure, and user-friendly alternative to traditional attendance methods.

V. CONCLUSION

The proposed drug traceability system successfully integrates blockchain, IoT, and artificial intelligence to address critical challenges in pharmaceutical supply chains. By enabling real-time tracking and secure verification, the system reduces the risks associated with counterfeit drugs and non-compliant deliveries. The use of blockchain ensures data immutability and transparency, while AI models assist in anomaly detection and counterfeit identification with high accuracy. IoT sensors and GPS modules provide continuous monitoring of environmental conditions and location tracking during shipment.

The system is capable of generating instant alerts to stakeholders in case of violations, ensuring timely corrective action. The modular design allows easy scalability and adaptation to various pharmaceutical environments. Test evaluations across diverse scenarios demonstrate reliable performance, strong detection precision, and regulatory compliance. This traceability framework provides a powerful solution to enhance patient safety, streamline operations, and support global healthcare goals.

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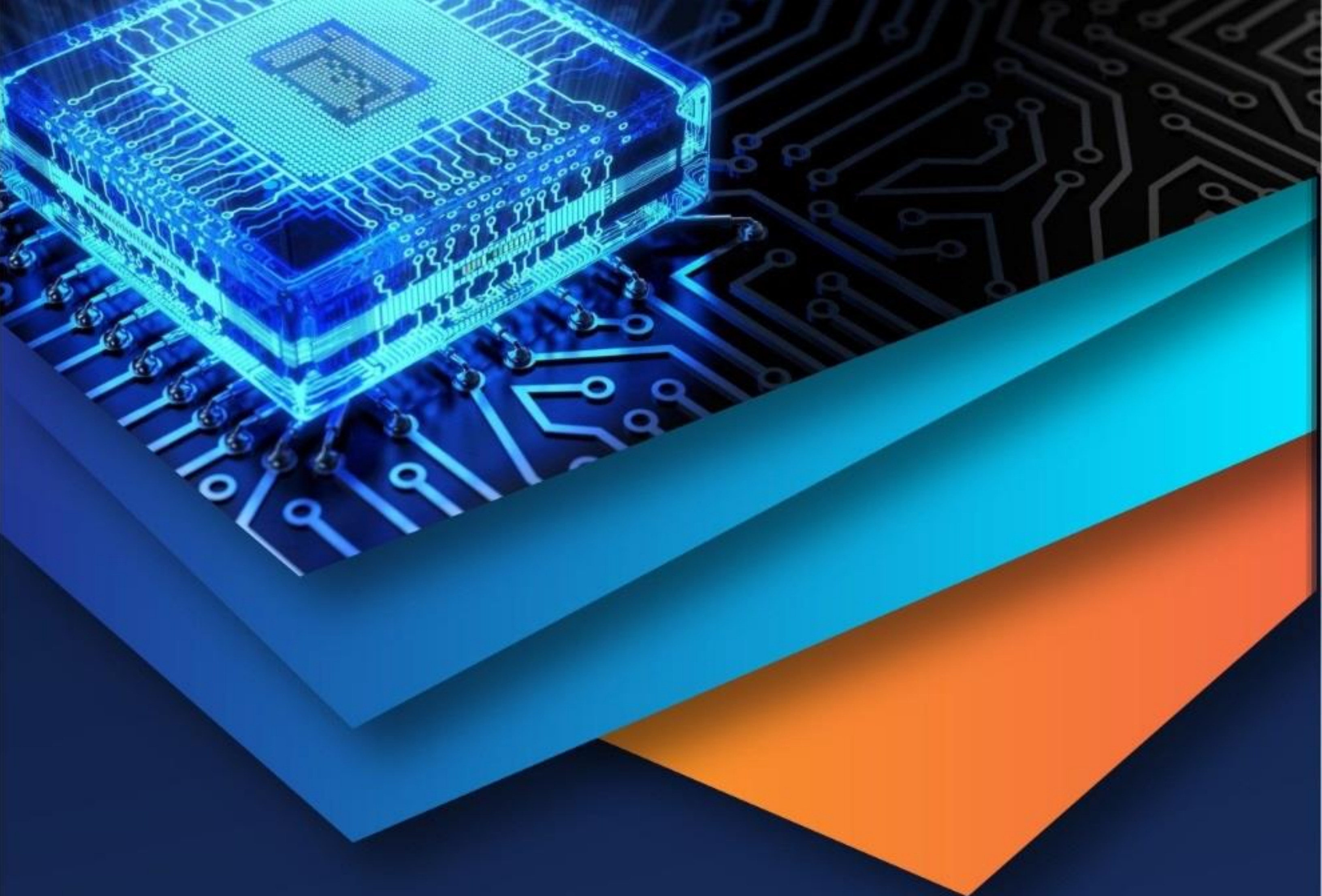

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