TRACKING AND VERIFICATION OF DRUGS USING BLOCKCHAIN: A REVIEW

BY

Okunlola, Babatunde Cyrus & Aro, Taye Oladele
Department of Computer Science, Al-Hikmah University, Adeta, Kwara State, Nigeria.
Email: cyrusokunlola@gmail.com | taiwo774@gmail.com

Abstract

Counterfeit and substandard drugs remain a serious global health threat, particularly in low- and middle-income countries where supply chains oversight is limited. This review examines the current landscape of blockchain applications for tracking and verifying drugs across pharmaceutical supply chains. Using a systematic literature search of peer-reviewed and grey sources (2020–2025) across major databases and project whitepapers, relevant studies and pilot projects were selected and synthesized. The review shows that blockchain often combined with IoT and smart contracts offers clear advantages for provenance tracking, unit-level serialization, anti-tampering, cold-chain monitoring, and auditability for regulatory compliance. Common platforms include permissioned systems (Hyperledger Fabric, Sawtooth, Multichain) and public frameworks (Ethereum, VeChain). However, most solutions remain at prototype or pilot scale; widespread adoption is constrained by scalability, interoperability with legacy systems, data-privacy concerns, regulatory misalignment, stakeholder governance issues, and cost especially in resource-limited settings. The paper concludes by recommending more real-world pilots, regulatory-technology co-design, interoperability standards, and targeted studies in low-resource contexts to move blockchain from promising pilots to sustainable, large-scale deployments.

Keywords: blockchain; drug traceability; pharmaceutical supply chain; serialization; drug verification

Introduction

Counterfeit drugs significantly impact global pharmaceutical supply chains, with research indicating that in underdeveloped countries, up to 40% of drugs are fake or adulterated (Madalsa Kumar, 2023), counterfeiting of drugs is leading to not only economic loss but is also playing its part in the morbidity and mortality of patients (Pathak et al., 2023). Existing verification and tracking systems in the pharmaceutical supply chain face issues such as vulnerabilities in security, inefficiencies leading to medicine shortages (Shetty et al., 2022), these systems are vulnerable to data breaches and manipulation, compromising the integrity of drug information (Chaabaoui et al., 2024a). Blockchain is a technology that allows users to validate, keep and synchronize the content of a transaction ledger that is replicated across multiple users. In other words, blockchain is a decentralized transaction and data management technology (Ali et al., 2021). To deal with the issue of counterfeit drugs, blockchain technology has the potential to provide pragmatic solution for drug traceability and provenance in a secure and immutable manner (Uddin et al., 2021).

The frequency of counterfeit drugs and consumables is a critical issue, threatening public safety and economic stability. Counterfeiting in pharmaceutical products is an increasing worldwide dilemma with a profound impact on lower income countries (LIC) and lower middle-income countries (LMIC) (Caudron et al., 2008). This malpractice not only poses health risks, potentially causing diseases or even death, but also leads to financial loses for (Yiannaka, 2023). Counterfeit drugs and adulterated consumable products directly endanger lives WHO estimates that of the 1 million deaths that occur each year due to malaria, 0.2 million of them are the result of counterfeit anti-malarial drugs (Keeping It Real About International Policy Network, 2009).

Traditional systems often depend on fragmented databases, manual record-keeping, and low digital transparency, making them susceptible to unauthorized product entry and hindering real-time traceability (Ettaloui et al., 2024). The integration of blockchain technology into pharmaceutical supply chains holds significant potential to address and resolve traditional supply chain challenges (Ghadge et al., 2023b).

Literature Review

Pharmaceutical Supply Chain

The pharmaceutical supply chain is a complex, multi-layered system facing challenges like fluctuating demand, regulatory requirements, and logistical constraints (Adeleke Damilola Adekola & Samuel Ajibola Dada, 2024), it encompasses the production, distribution, and delivery of pharmaceutical products, starting from raw material sourcing to manufacturing, followed by distribution through wholesalers and pharmacies, while ensuring regulatory compliance and addressing challenges like drug fraud and counterfeiting (Sharma Meenu, 2023).

Related Works

Previously, multiple studies have systematically examined blockchain applications in healthcare and broader supply chain contexts, while more targeted analyses have focused on the technology's readiness and positioning within specific healthcare systems.

(Chaabaoui et al., 2024b) conducted a systematic review of blockchain applications in pharmaceutical supply chain traceability and security, highlighting frameworks, technical barriers, and emerging use cases across regional and functional contexts. (Tiwari et al., 2024) explored blockchain's role in enhancing security, transparency, and operational efficiency in pharmaceutical supply chains. Their review emphasizes benefits such as automated traceability, improved collaboration among stakeholders, and proposed solutions to scalability and legacy systems integration.

(Akram et al., 2024) presented a comprehensive literature-based analysis on using blockchain as a tool for managing pharmaceutical supply chains, focusing on its ability to enable end-to-end traceability and improve regulatory oversight across multiple stakeholders. (Dhingra et al., 2024) contribute a comprehensive review focused on blockchain applications in healthcare supply chains (IEEE Access), synthesizing recent trends, key drivers, and cross-sector comparisons. (Ghadge et al., 2023) examine blockchain implementation in pharmaceutical supply chains (PSC) and develop a conceptual framework outlining enablers, inter-organizational coordination, and governance mechanisms. They highlight gaps in empirical deployment and scalability across diverse contexts. (Mirdad et al., 2023) offer a focused systematic review of pharmaceutical supply chains via text-mining analysis. They identify research gaps and opportunities for future work, particularly in emerging economies and interdisciplinary integration.

(Elangovan et al., 2022) present a broader healthcare sector systematic review (JMIR Med Inform), cataloguing blockchain use across electronic health records, biomedical research, remote monitoring, and pharmaceutical supply chains. They distill common motivations such as data integrity, non-repudiation, and access control. (Jadhav & Deshmukh, 2022) systematically categorized healthcare blockchain products and major industry players, mapping applications to potential and integration challenges, although context-specific details were limited. (Zakari et al., 2022) conducted a systematic literature review of 38 articles published between 2016 and 2021 on blockchain use in the pharmaceutical industry. Their work identifies key technologies, application domains, adoption barriers, and proposes future research directions in traceability, transparency, and trust enhancement.

Blockchain Technology Fundamentals

Blockchain is a decentralized solution which does not require any third-party organization in the middle (Karthika & Jaganathan, 2019). The information about every transaction ever completed in Blockchain is shared and available to all nodes. This attribute makes the system more transparent than centralized transactions involving a third party (Yli-Huumo et al., 2016).

There exists a variety of Blockchain classifications predicated on their functionality and unique characteristics:

(i). Public blockchains
(ii). Private blockchains and
(iii). Consortium blockchains.

Public blockchains are fundamentally decentralized and permit any individual to join the network and partake in their governance (Grandjean et al., 2023). In contrast, private blockchains restrict access solely to invited individuals from a singular organization, who are permitted to join the network and oversee its operations (Bahalul Haque & Rahman, 2020).

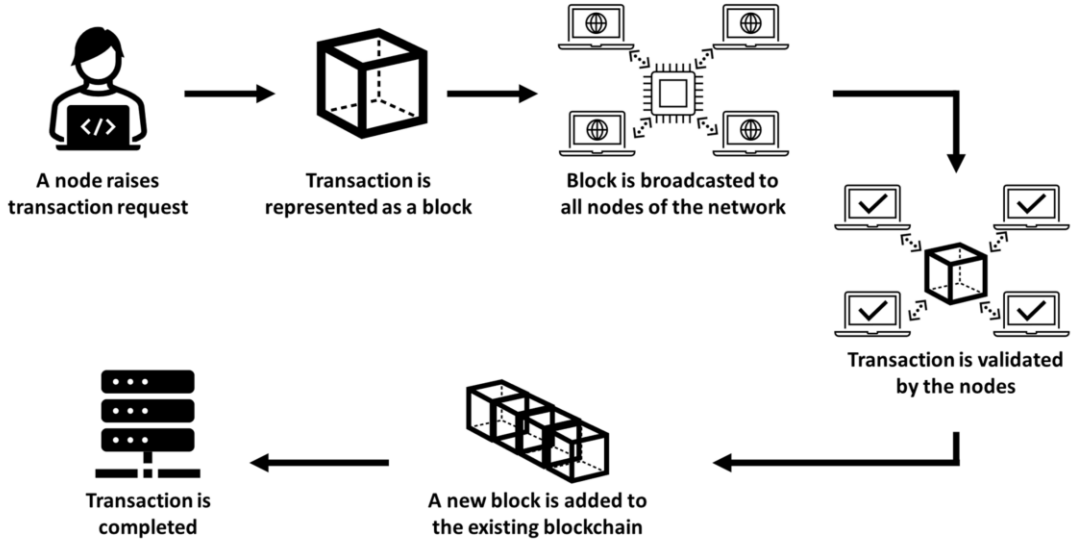

Figure. 2.3 Transaction Flow in a Blockchain Network (Raja Santhi & Muthuswamy, 2022).

Some key features of blockchain:

Immutability:

Any transaction that is incorporated into a blockchain network possesses the attribute of immutability, signifying that it is impervious to alteration or manipulation. Furthermore, both the initial erroneous transaction and the subsequently recorded transaction will be accessible to the network participants in a chronological sequence with an appropriate timestamp (Raja Santhi & Muthuswamy, 2022).

Decentralization:

Decentralization constitutes a fundamental characteristic of blockchain technology, indicating that it lacks a singular authority to exert control and does not depend on a centralized server for data management or storage within the framework (Dorri et al., 2021).

Distributed Ledger:

A distributed ledger represents a database wherein data is disseminated, replicated, and synchronized among the participants of the network, blockchain operates on the principles of decentralization and distribution among nodes. Additionally, within a shared ledger, as a transaction can be recorded only once, it effectively mitigates the risk of duplication. (Lee et al., 2021).

Blockchain Use Cases in Pharmaceutical Supply Chain

Blockchain technology has emerged as a disruptive instrument with diverse applications designed to tackle persistent challenges in pharmaceutical supply chains, including counterfeit medications, fragmented data systems, and inadequate traceability.
One of the core applications of blockchain in the pharmaceutical industry is provenance tracking, provenance tracking is used to record vital information such lifecycle of a drug from manufacturing to dispensation (Burgess et al., 2022)
Serialization is the process of assigning a unique identification number on each individual package of the medicine and applying an anti-tampering device (Trajanovska et al., 2022).

Methodology

Research Design

To review some of the existing blockchain-based frameworks and use case studies, this study utilizes a systematic review methodology to identify, evaluate and synthesize existing knowledge and applications of blockchain in pharmaceutical supply chain management, with particular focus on tracking and verification of drugs. The review examined how blockchain based solutions have been conceptualized, simulated, or implemented in various contexts. The goal was to map, categorize, and critically assess the breadth of solutions, identifying gaps, benefits, and emerging patterns.

Literature Search Strategy

In this study, a comprehensive search strategy was developed to ensure good coverage of peer-reviewed literature and relevant technical/grey literature. The search was carried out across both academic and industrial domains. The academic databases used included Scopus, IEEE Xplore, PubMed, ScienceDirect (Elsevier), SpringerLink, and Google Scholar. In addition, grey literature and technical documentation were sourced from reputable platforms such as the official websites and whitepapers of MediLedger, VeChain, IBM Blockchain, and OriginTrail, as well as regulatory organizations like the World Health Organization (WHO), GS1, the U.S. Food and Drug Administration (FDA), and Indonesia's BPOM.

To extract relevant research articles, the search utilized set of focal and contextual keywords and Boolean operators such as "blockchain" AND "pharmaceutical supply chain", "drug traceability" OR "medicine verification", and "blockchain framework" AND "case study. The search was limited to English language publications, within predefined inclusion criteria comprised papers published between 2020–2025, and document types including peer-reviewed journal articles, conference papers, technical reports, and whitepapers.

Inclusion and Exclusion Criteria

To maintain the relevance, quality, and focus of the literature reviewed, a clear set of inclusion and exclusion criteria was established. Studies were included if they specifically addressed the application of blockchain technology within pharmaceutical supply chains, particularly those focused on drug tracking, verification, serialization, or anti-counterfeiting measures. Conversely, articles were excluded if they focused on general blockchain applications unrelated to pharmaceutical logistics, lacked any form of practical implementation or use-case analysis. This screening process ensured that the review captured studies with substantive contributions to the development and application of blockchain in pharmaceutical traceability. The results were limited to "peer-reviewed" journal articles only. It was also limited to "full-text" journal articles that were available at a price or free of cost. The study included "review articles" and "research articles" while excluding book chapters and other kinds of articles.

Data Extraction & Synthesis

After removing the duplicates and excluding literature from the selected databases, each paper was carefully synthesized by considering the title, keywords, and abstract to select 11 papers that were found to be relevant to the study.

Summary and Discussion

The reviewed studies show growing interest in using blockchain to improve transparency, traceability, and security in pharmaceutical supply chains. Projects like MediLedger (Chien et al., 2020) and BRUINchain target the U.S. Drug Supply Chain Security Act (DSCSA) by enabling drug serialization, saleable returns checks, and real-time transaction logs. These pilots show blockchain's ability to meet regulatory needs while reducing paperwork. Similar work by Nawaz et al. (2024) and Uddin (2021) uses Hyperledger with IoT cold chain monitoring to protect temperature-sensitive drugs and keep permanent compliance records.

Other systems, such as VeChain DNV GL (2020) and OriginTrail (2021), assign each drug batch a unique digital identity linked to decentralized data networks, allowing different actors manufacturers, distributors, regulators, and consumers to share trusted data. Gomasta et al. (2023) and Liu et al. (2021) show smart contracts automating checks and alerts for anomalies.

Most solutions remain at pilot stage, with few scaled commercial rollouts. Barriers include integration with old systems, data governance and privacy issues, blockchain scalability limits, and lack of global regulatory alignment. Without cross-border standards, adoption will stay fragmented. Future work must focus on moving from pilots to sustainable, large-scale systems that work internationally and involve all supply chain actors.

Challenges Identified

While blockchain shows strong potential for improving pharmaceutical supply chains, several practical barriers hinder large-scale adoption. Scalability remains a major challenge, as many systems that work well in pilots struggle to operate at national or global levels due to high computational and infrastructure demands (Musamih et al., 2021; Nawaz et al., 2024; Liu et al., 2021). Interoperability is another hurdle, with blockchain often difficult to integrate into existing systems used by pharmaceutical companies, healthcare providers, and regulators (Tiwari et al., 2024; Uddin, 2021). Financial constraints, especially in low- and middle-income countries with limited infrastructure and expertise, further restrict adoption (Attaran, 2022; Mirdad & Hussain, 2021). Finally, while many studies propose promising models, most remain at the pilot stage, with few real-world deployments or long-term results reported (Clauson et al., 2018; Chien et al., 2020; Gomasta et al., 2023).

Research Gaps

Although research on blockchain in pharmaceutical supply chains is expanding, important gaps remain. A major limitation is the lack of real-world implementation studies. Most publications present theoretical models or simulations, but few document live deployments or evaluate long-term performance in operational settings. As a result, the practical challenges faced by end users and the scalability of these systems are still not well understood (Chien et al., 2020; Gomasta et al., 2023).
Regulatory integration is another underexplored area few examine in depth how blockchain solutions could be adapted to meet these legal standards or address potential regulatory conflicts (Akram et al., 2024; Chaabaoui et al., 2024).

Finally, interoperability and stakeholder trust are often mentioned but insufficiently analyzed. Designing systems that manufacturers, regulators, pharmacies, and patients are willing to adopt, and ensuring compatibility with existing supply chain processes, remain unresolved challenges. Addressing these questions is essential for moving blockchain applications from controlled research environments into routine, real-world use.

Future Research Directions

Future research endeavors focused on blockchain technology within pharmaceutical supply chains may progress in several intriguing avenues. The implementation of additional pilot evaluations and empirical case studies constitutes one of the most urgent necessities. While the existing theoretical frameworks provide valuable insights, it is imperative that researchers engage in close collaboration with governmental and industrial stakeholders to effectively assess blockchain systems within actual pharmaceutical environments. Such collaboration would promote a shift from simplistic simulations, thereby enabling a thorough comprehension of the operational effectiveness of these technologies in real-world contexts, including both their successful applications and their limitations. (Chien et al., 2020; Dhingra et al., 2023).

Conclusion

This review shows how blockchain has developed from a theoretical curiosity into a collection of useful tools that have the real potential to enhance the integrity of pharmaceutical supply chains. In every study that was looked at, blockchain consistently improved provenance visibility, made unit-level verification possible, and, when combined with IoT, supported cold-chain assurance and more detailed audit trails. These capabilities tackle actual harms, such as diversion, counterfeit medications, and opaque recall procedures that put patients at risk and erode confidence.

Nevertheless, this technology is not a cure-all. The separation between pilots and implementation is clear given that most Indigenous implementations remain either local, experimental or simulated. Closing this gap depends on agreement on governance models, harmonizing standards across jurisdictions, and creating sustainable business models that have viability in low- and middle-income contexts showing that blockchain can work in theory particularly in such environments.

The next steps are simple and practical, the running of more real-world pilots. The community should invest in interoperability layers and lightweight node designs appropriate for constrained environments; regulators and industry should co-design compliance hooks (e.g., smart contract templates aligned to DSCSA/FMD/WHO guidance); and researchers and practitioners should prioritize strong field pilots with longitudinal evaluation.

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