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# A Comparative Evaluation Of Blockchain Platforms For Drug Supply Chain Management

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***Abstract:*** The global pharmaceutical industry faces persistent challenges, notably the proliferation of counterfeit drugs, which poses severe public health risks and economic losses. Traditional supply chain frameworks frequently exhibit deficiencies in the requisite transparency and traceability, which are essential for effectively addressing these challenges. Blockchain technology, characterized by its fundamental attributes of immutability, transparency, and cryptographic security, presents a viable approach to augment the integrity of the pharmaceutical supply chain. This manuscript seeks to deliver an exhaustive comparative analysis of leading blockchain platforms, particularly focusing on Hyperledger Fabric and Ethereum, to assess their applicability in the management of drug supply chains. This study is founded solely on a comprehensive examination of scholarly literature, evaluating essential factors including performance metrics (throughput and latency), security protocols, scalability attributes, consensus algorithms, privacy considerations, and financial ramifications. Key findings indicate that Hyperledger Fabric generally outperforms private Ethereum in invoke (write) functions, demonstrating higher throughput and significantly lower latency for operations like creating users or transferring money. Conversely, private Ethereum excels in query (read) operations due to its account-based ledger model, offering lower latency. While both platforms show scalability limitations, Hyperledger Fabric is better suited for structured enterprise applications requiring high transaction throughput and permissioned access, whereas private Ethereum's performance can be inconsistent due to gas fees and computational overhead, particularly for complex operations. The study concludes by recommending the most suitable platform for the pharmaceutical industry, discussing the practical implications and trade-offs.

***Index Terms* -** Blockchain, Drug Supply Chain, Counterfeit Drugs, Hyperledger Fabric, Ethereum, Traceability, Scalability, Performance, Phar Blockchain, Drug Supply Chain, Counterfeit Drugs, Hyperledger Fabric, Ethereum, Traceability, Scalability, Performance, Pharmaceutical Industry.

## I. INTRODUCTION

The pharmaceutical industry constitutes an essential element of worldwide healthcare, tasked with the manufacturing and dissemination of life-preserving pharmaceuticals. Nevertheless, the intricacy of its supply chain, frequently encompassing numerous stages and diverse geographical areas, introduces substantial vulnerabilities. This complex framework is susceptible to data losses and operational impediments, thereby complicating the maintenance of a resilient and infallible structure. [1]. A primary concern in this sector is the widespread issue of drug counterfeiting, which leads to poor therapeutic efficacy, drug resistance, and potentially severe health consequences, including allergic disorders, serious injury, or even death from harmful or inactive ingredients [2] .The World Health Organization (WHO) estimates that 10% of the worldwide pharmaceutical market consists of counterfeit pharmaceuticals, posing a grave threat to patient safety and public health. India, for instance, a major producer and exporter of medicines, faces a significant market for spurious and counterfeit medications, with estimates suggesting that between 12% and 25% of all pharmaceuticals supplied in the country are fake. Individuals engaging in criminal activities take advantage of illicit networks, encompassing the dark web, to produce and disseminate substantial quantities of counterfeit pharmaceuticals, an issue that has been intensified by worldwide disturbances such as the COVID-19 pandemic. [2]

In order to effectively tackle these pressing issues, blockchain technology has arisen as a transformative and pioneering remedy. The distinctive amalgamation of attributes, including a decentralized framework, distributed nodes, and a storage mechanism, consensus protocols, smart contracts, and asymmetric cryptography, guarantees the security, transparency, and visibility of the network. By establishing an immutable and tamper-resistant distributed ledger, blockchain technology is capable of furnishing an incontrovertible record of each event and transaction, thereby facilitating improved traceability, authenticity, and trust throughout the supply chain. [1] The deployment of blockchain technology has the potential to foster comprehensive visibility throughout processes, bolster data integrity, optimize decision-making capabilities, and enable fluid integration between the tangible and digital realms, thus directly addressing challenges such as product counterfeiting while promoting effective traceability and oversight.[3]

Given the immense potential of blockchain to transform supply chain functions and the critical need for secure and transparent drug distribution, a comparative evaluation of leading blockchain platforms is essential. This scholarly article endeavors to fulfill the necessity for an exhaustive examination that will facilitate the identification of the most appropriate blockchain technology for implementation within the pharmaceutical supply chain.This research undertaking aspires to elucidate the subsequent inquiries:

1. How does Hyperledger Fabric and Ethereum contrast with respect to performance metrics (throughput, latency), security, scalability, privacy, cost considerations, and consensus mechanisms pertinent to drug supply chain applications?
2. Which of these technological platforms is optimally positioned to meet the distinct requirements and challenges inherent in the pharmaceutical supply chain, particularly in relation to the detection of counterfeit pharmaceuticals and ensuring traceability?
3. What are the practical implications and trade-offs associated with adopting the recommended blockchain platform for pharmaceutical industry stakeholders?

## II. Literature Review

The utilization of blockchain technology within diverse sectors has been rigorously examined, elucidating its considerable capacity to revolutionize supply chain management processes.

### *Blockchain in Supply Chain Management*

Blockchain represents a decentralized, distributed, and immutable ledger system that is capable of securely storing and recording data and transactions across a peer-to-peer network.[1] Its core features, including transparency, authenticity, trust, security, and the ability to reduce costs and disintermediation, make it highly beneficial for Supply Chain Management (SCM). Blockchain technology facilitates instantaneous order reconciliation and the automation of production processes via intelligent contracts. It has the potential to alleviate risks related to intellectual property theft, cyber intrusions, and disputes arising from contractual obligations, thereby enhancing the robustness of supply chains by diminishing the effects of disruptions and offering multiple layers of protection. Key functional areas of the supply chain that can be improved with blockchain include provenance, resilience, reengineering, security enhancement, business process management, and product management. For instance, blockchain and IoT aid in granular provenance, ensuring certifiability, traceability, and authenticity of product information across complex, inter-organizational supply chains.[3].

### *Blockchain in Drug Supply Chain*

The healthcare industry, encompassing pharmaceuticals, encounters considerable obstacles including disjointed supply chains, suboptimal data management practices, insecure data exchange, apprehensions regarding data privacy, and the proliferation of counterfeit pharmaceuticals. The application of blockchain technology holds the potential to mitigate these challenges by augmenting patient outcomes, reducing expenditures, enhancing compliance, and guaranteeing the security and transparency of healthcare-related data. Specifically for pharmaceuticals, blockchain can improve medicine and vaccine traceability, assist transparent data sharing in clinical trials, and help manage drug recalls. Pharmacosurveillance blockchain systems have been proposed to transform the entire distribution chain in the pharmaceutical industry to combat drug counterfeiting. Hyperledger Fabric, in particular, has been identified for enhancing medical supply chains and drug records. QR codes, combined with blockchain, can provide unique IDs for each product, ensuring traceability from manufacturer to pharmacy and helping to identify fake medications. Private cloud-based blockchain systems can ensure visibility and minimize fraud in sensitive areas like blood management systems [[3]

### *Comparative Studies on Blockchain Platforms*

Numerous scholarly investigations have assessed and contrasted various blockchain platforms. Dutta et al. (2020) executed an exhaustive analysis of the applications of blockchain technology across diverse industrial supply chain sectors, encompassing healthcare, energy, food, and finance.[3] . Lingayat et al. (2021) specifically compared existing proposed architectures of blockchain and IoT-based supply chain management systems, focusing on Hyperledger Fabric and Ethereum for pharmaceutical supply chains. They highlighted that while both provide a base for accountability, Hyperledger Fabric is "better suited for building a decentralized platform for tracking and traceability" in the pharmaceutical supply chain due to its scalability and identity management system. Shen and Pena-Mora (2018) highlighted Ethereum and Hyperledger Fabric as the most commonly used platforms for blockchain applications. [3].

More recent comparative analyses, such as those by Kahmann et al. (2023) and Khan et al. (2025), delve into the performance metrics of Hyperledger Fabric and Ethereum. Kahmann et al. (2023) compared Hyperledger Fabric (v2.3) and Ethereum (Besu v23.1.1) along with DAG-based platforms, noting that public Ethereum (v1.0) had a theoretical maximum of 30 Transactions Per Second (TPS), while Hyperledger Fabric showed significantly higher performance in some contexts. [4]. Khan et al. (2025) conducted a detailed performance comparison of Hyperledger Fabric (v2.5) and private Ethereum (Geth v1.13.5), focusing on smart contract execution under varying transaction loads and network sizes. [4].

### *Identification of Research Gaps*

Despite the growing body of literature, several research gaps persist. While many studies highlight the potential of blockchain, details about actual or prototype implementation are largely missing. [3] There is a need for more empirical studies and case-based analyses of blockchain adoption and implementation, especially from startups and retail chains. Existing comparative studies sometimes lack smart contract-level benchmarking under various workloads or a systematic analysis of the latest platform versions under diverse real-world financial scenario.[4]. Furthermore, there is an ongoing need to explore whether a common standard across different blockchain platforms should be developed to link them at a global level to address interoperability issues. The reluctance of organizations to share sensitive information on a global platform also acts as a major obstacles.[3]

## III. Methodology

This comparative evaluation adopts a quantitative research design approach by synthesizing findings from various academic sources that present empirical data on blockchain platform performance.

### *Data Sources*

The data sources utilized in this investigation comprise scholarly journal articles. These articles were discerned through comprehensive literature reviews concentrating on the application of blockchain technology within supply chains, with a particular emphasis on the pharmaceutical industry, alongside comparative analyses of various blockchain platforms. The blockchain platforms chosen for this comparative analysis are Hyperledger Fabric and Ethereum.

### *Evaluation Parameters*

The comparative evaluation of Hyperledger Fabric and Ethereum is conducted using the following key parameters.

***Performance:***

1. **Transactions Per Second (TPS):** Quantifies the volume of transactions that a platform is capable of processing within a one-second interval.
2. **Latency:** Quantifies the duration required for the confirmation of a transaction (Confirmation Time - Submission Time), typically measured in milliseconds.
3. **Security:** Evaluates the frameworks in place for ensuring data integrity, authentication, confidentiality, privacy, and resilience against tampering.
4. **Scalability:** Analyzes the platform's capacity to accommodate escalating transaction volumes and network expansion (number of nodes/peers).
5. **Consensus Mechanism:** Investigates the algorithms employed to validate and incorporate transactions into the ledger (e.g., Proof of Work, Proof of Stake, Raft, PBFT).

6. **Privacy Features:** Evaluates the extent of data visibility and access control mechanisms provided by the platform (e.g., public versus permissioned networks).
7. **Cost:** Examines the financial implications associated with operational and implementation expenditures, including transaction fees (e.g., gas fees for Ethereum).
8. **Regulatory Compliance:** Addresses the complexities and requirements pertaining to legal frameworks necessary for the effective implementation of blockchain technology.

## IV. OVERVIEW OF SELECTED BLOCKCHAIN PLATFORMS

### *Hyperledger Fabric*

Hyperledger Fabric (Fabric) is an open-source, permissioned blockchain framework designed for enterprise-grade applications. It is one of many blockchain projects under the Hyperledger Foundation.

**Architecture and Features:** Fabric employs a private/permissioned network architecture where participants have different roles and access is controlled via a Public Key Infrastructure (PKI) [5].It does not require a native token for consensus, relying instead on implicit trust among peers. The network consists of Channels (hosting blockchain instances), Peers (maintaining integrity, divided into Endorsement and regular Peers), and Orderer nodes (responsible for consensus, often using Raft consensus algorithm). Fabric enables developers to execute bespoke smart contracts, referred to as Chaincode, authored in versatile programming languages such as Java, JavaScript, and Golang, while utilizing Docker containers to facilitate isolated execution. This modular framework furnishes a secure, scalable, and tailored blockchain infrastructure [6].

**Use in Drug Supply Chain:** Hyperledger Fabric has been specifically proposed and used to enhance the medical supply chain and drug records to combat drug counterfeiting, as seen in systems designed for Pharmacosurveillance [7]. Its permissioned nature and robust identity management make it suitable for environments where data privacy and control are paramount, such as tracking and traceability in the pharmaceutical supply chain [1].Walmart and IBM have used Hyperledger Fabric for food traceability, [8]demonstrating its capability for similar applications in pharmaceuticals.

### *Ethereum*

Ethereum constitutes an open-source blockchain framework that enhances the functionalities of Bitcoin by incorporating the notion of smart contracts [9]. It functions within the framework of an Ethereum Virtual Machine (EVM), which is a decentralized state machine that facilitates the preservation and execution of bespoke smart contracts [10].

**Smart Contracts and Public Nature:** Smart contracts deployed on the Ethereum blockchain represent autonomous executable programs, predominantly developed in the Solidity programming language, that inherently execute the stipulated terms of an agreement upon the fulfillment of predetermined conditions. These contracts operate within a decentralized framework, thereby guaranteeing transparency and safeguarding against manipulation, while also facilitating the elimination of intermediaries, consequently augmenting security, efficiency, and the degree of automation. The main Ethereum platform is a public network where any entity can join, generate, and validate blocks. However, a private Ethereum network (using clients like Geth) can be deployed where only whitelisted IP addresses can join, offering a controlled environment for experimentation and enterprise applications [11].

**Consensus:** In its nascent phase, Ethereum 1.0 implemented a Proof-of-Work (PoW) consensus mechanism, which proved to be computationally intensive and resulted in elevated energy consumption. [12]**.** Ethereum 2.0 has unveiled an innovative Proof-of-Stake (PoS) protocol known as "Casper" which aims to enhance operational efficiency and scalability. [13]

**Use in Drug Supply Chain**: Ethereum, through its smart contract functionality, has been utilized in various supply chain contexts for managing transactions between senders and receivers, especially when integrated with IoT sensors for monitoring shipping conditions like temperature and humidity of medicine containers [1]. It has been used for supply chain provenance, where traceability ontologies and constraints are studied on the Ethereum blockchain. Price transparency has also been guaranteed through pilot implementations of smart contracts on the Ethereum network [7].

### *Comparative Analysis*

This section provides a detailed comparative analysis of Hyperledger Fabric and private Ethereum across the defined criteria, synthesizing data and insights from the provided sources.

*Table 1 Comparative Analysis of Hyperledger Fabric and Ethereum*

| S.N. | Criteria | Hyperledger Fabric | Private Ethereum | Reference |
|---|---|---|---|---|
| 1 | Architecture | Permissioned/Private Blockchain: Access is restricted and requires authentication via PKI; participants have defined roles | Permissioned (Geth client): Can be deployed as a private network with whitelisted IP addresses, though public Ethereum is permissionless | [12] |
| 2 | Consensus Mechanism | Raft (leader-follower model) or PBFT: More streamlined, designed for private networks, resulting in faster transaction processing and improved throughput | Proof of Stake (PoS): (Casper for Ethereum 2.0). PoW was used in older versions, which is computationally expensive. PoS involves a complex validation process | [14] |
| 3 | Smart Contract | Chaincode: Written in general-purpose languages (Java, JavaScript, Golang). Utilizes Docker containers to facilitate a lightweight, isolated, and efficient execution environment, thereby mitigating interference and augmenting resource efficiency. | Solidity: Used for coding contracts. Does not use Docker containers, which can lead to higher resource contention, affecting throughput and latency | [15] |
| 4 | Ledger Model | World-state model: Maintains the current state of the entire blockchain, optimizing performance in transaction-intensive applications | Account-based model: Each account maintains its balance and state, more efficient for querying user data | [4] |
| 5 | Performance (TPS) | Invoke (Write) Functions (CreateUser, TransferMoney, IssueMoney): Significantly higher throughput. Peak throughput for CreateUser at 1821.23 TPS (2 peers), TransferMoney and IssueMoney at 1619.76 TPS (4 peers) for 1000-batch transaction | Invoke (Write) Functions: Significantly lower throughput and higher latency than Fabric for these operations. CreateUser peak at 78.89 TPS (16 peers). Exhibits fluctuations and inconsistencies, especially with increasing peers and batch sizes | [4],[12] |
| 6 | Latency | Invoke (Write) Functions: Achieves significantly lower latency (up to 14x for CreateUser and 17x for IssueMoney with up to 8 peers) | Invoke (Write) Functions: Latency worsens significantly as network grows beyond 8 peers for CreateUser and IssueMoney due to PoW-based processing (older versions) or block finalisation/gas fee mechanics | [4],[12] |
| 7 | Security | High: Permissioned network access via PKI, making it highly secure and less susceptible to external manipulation. Immutable ledger, cryptographic design ensures data integrity. | High: Employs cryptographic safeguards, permanence, and distributed architecture. Public variant relies on a large number of nodes for security. Private variant relies on whitelisted access. Challenges exist with sharding security. | [11] |
| 8 | Scalability | Efficient for moderate transaction volumes: Scales | Processes higher transaction volumes (up to 10,000): Can handle up to 10,000 transactions | [12] |

| S.N. | Criteria | Hyperledger Fabric | Private Ethereum | Reference |
|---|---|---|---|---|
| | | efficiently within moderate transaction volumes, | in batches, but with performance fluctuations due to gas fees and computational overhead. Struggles with write-heavy transactions at scale and exhibits erratic throughput patterns | |
| 9 | Privacy | High: Private/permissioned network architecture provides role-based access to data, limiting visibility to authorized parties, ensuring confidentiality for sensitive information | Lower in Public, higher in Private: Public Ethereum stores data as a public ledger, offering less privacy. Private Ethereum (Geth) offers enhanced privacy and control through whitelisted access. Consortium blockchains can balance public and private features. | [16] |
| 10 | Cost | Non-trivial implementation and operations cost: Does not require a native token for consensus, but overall implementation and operational costs can be significant. Docker container usage contributes to resource efficiency | Non-trivial implementation and operations cost, including gas fees: Initial versions had inefficient mining (PoW). Performance fluctuations due to gas fees indicate challenges for computationally intensive smart contracts | [4] |
| 11 | Regulatory Compliance | Challenges exist for blockchain in general, with legal and regulatory frameworks often unclear and needing government involvement for standardization | Faces similar challenges regarding unclear laws and regulations. | [17] |

***Suitability for Drug Supply Chain Requirements***

For drug supply chain management, the paramount requirements are robust traceability, authenticity, and security to combat counterfeiting, alongside efficient data processing and controlled access for stakeholders (manufacturers, wholesalers, distributors, pharmacists, regulators, and consumers [1].

**Counterfeit Prevention and Traceability:** Both platforms can support traceability by recording transactions and product information. Hyperledger Fabric's permissioned nature and high write throughput are highly advantageous for consistently recording every step of the drug's journey, from raw material to patient, ensuring an auditable and immutable record that prevents illicit alterations. The ability to integrate QR codes and unique IDs, as proposed for drug tracking, aligns well with Fabric's strengths in capturing and securing such data efficiently [18].

**Data Privacy and Control:** The pharmaceutical sector manages exceptionally confidential information (e.g., patient documentation, proprietary compositions, contractual agreements regarding supply). Hyperledger Fabric's private, permissioned architecture with role-based access offers superior control over data visibility, making it inherently more suitable for maintaining confidentiality while allowing necessary transparency for authorized parties like regulators. While private Ethereum can achieve this, its public roots might raise more inherent concerns regarding data exposure in complex, multi-party enterprise settings [19].

**Operational Efficiency:** The drug supply chain requires high transaction efficiency. Hyperledger Fabric's superior performance in invoke operations (e.g., recording new shipments, changes in custody) translates directly to faster and more reliable updates to the ledger, which is critical for real-time tracking and preventing delays. Although Ethereum excels in query operations, the consistent high throughput for write operations is generally more critical for maintaining a continuously updated, secure chain of custody.[12]

### *Case Studies*

**Hyperledger Fabric:** Has been explicitly used for Pharmacosurveillance systems and enhancing drug records. Walmart's use of Hyperledger Fabric for food traceability demonstrates its real-world applicability for secure and trusted supply chain data, which is highly analogous to the drug supply chain [12].

**Ethereum:** Modum.io has used Ethereum for quality control during medicine shipping, leveraging IoT sensors to store temperature and humidity data on its public blockchain.[1]. Pilot implementations on the Ethereum network have also been used to ensure price transparency in product distribution. While these show its utility, they often involve public blockchain (or private deployments of public tech), which may not offer the same level of granular control and consistency as Hyperledger Fabric for complex, permissioned enterprise needs [19].

## V. DISCUSSION

Interpreting the comparative findings, it becomes evident that the choice of blockchain platform for drug supply chain management involves careful consideration of the specific needs, trade-offs, and practical implications for industry stakeholders.

### *Interpretation of Comparative Analysis*

The analysis reveals distinct strengths for both Hyperledger Fabric and private Ethereum. Hyperledger Fabric's architecture is inherently designed for enterprise use cases where permissioned access, high transaction throughput for state-changing operations, and predictable performance are paramount. Its use of the Raft consensus mechanism and Docker containers for smart contract execution contributes to its efficiency and stability in handling write-heavy workloads, which are frequent in recording drug movements and custody changes. The clear advantage in invoke function latency and throughput positions Fabric as a strong candidate for maintaining real-time, tamper-proof records throughout the complex drug supply chain.

On the other hand, private Ethereum, with its account-based model, excels in querying data, offering faster retrieval for verification purposes. This could be beneficial for consumers or pharmacists quickly verifying a drug's authenticity by scanning a QR code and querying its history. However, its performance for write operations tends to be less stable and suffers from fluctuations, particularly due to gas fees and computational overhead, making it potentially less predictable for continuous, high-volume data recording in a complex enterprise setting. While it can process a large number of transactions, the consistency and predictability of write operations are critical for drug traceability.

### *Platform Best Suited for Drug Supply Chain Management and Why*

Considering the unique demands of the pharmaceutical supply chain, particularly the imperative for unquestionable traceability, stringent security, and controlled data access to combat counterfeiting and ensure patient safety, Hyperledger Fabric emerges as the most suitable platform.

**Reliable Record-Keeping:** Its superior performance in invoke (write) functions ensure that every transaction—from manufacturing to distribution and sale—is recorded quickly and reliably, creating a robust, immutable chain of custody. This is fundamental to identifying and preventing counterfeit drugs.[2]

**Enhanced Privacy and Control:** The permissioned nature of Hyperledger Fabric allows pharmaceutical companies to maintain strict control over who can participate in the network and what data they can access. This is vital for protecting sensitive business and patient information while still enabling necessary transparency for regulators and audited parties. [19]

**Scalability for Enterprise Needs**: While both platforms have scalability limitations, Fabric's structured approach and efficiency within typical enterprise transaction volumes (up to 1000 transactions per batch for write functions) are more aligned with the operational realities of a complex supply chain that needs predictable performance [4].

### *Trade-offs in Platform Selection*

**Read vs. Write Performance**: Choosing Hyperledger Fabric means prioritizing high-volume, consistent write operations over potentially faster read operations at lower transaction volumes. However, for traceability, the integrity and speed of writing new records are often more critical than the speed of querying existing ones.[4]

**Flexibility vs. Predictability:** While Ethereum's flexibility (e.g., general-purpose smart contracts) can be appealing, its fluctuating performance and reliance on gas fees introduce unpredictability in a mission-critical application like drug supply chain management. Hyperledger Fabric offers greater predictability and stability for defined enterprise workflows [4].

### *Practical Implications for Industry Stakeholders*

**Combating Counterfeiting**: Implementing Hyperledger Fabric would enable a robust system for generating unique QR codes or digital tags for each drug product at the manufacturing stage, with subsequent scans and signatures recorded by distributors, wholesalers, and pharmacists. This "Factory to Pharmacy" (FTP) traceability would make it significantly harder for counterfeit drugs to infiltrate the supply chain and easier to identify them at any stage, including by consumers through scanning [2].

**Enhanced Trust and Collaboration**: The transparent and immutable nature of the ledger would foster greater trust among all stakeholders—manufacturers, logistics providers, pharmacists, and even consumers—by providing verifiable information about the drug's origin, journey, and authenticity. This could streamline business processes and improve relationships.

**Regulatory Alignment**: While regulatory frameworks for blockchain are still evolving, a permissioned platform like Hyperledger Fabric allows for the integration of specific access controls and auditing mechanisms that can align with existing or future pharmaceutical regulations, facilitating easier compliance compared to fully public, permissionless systems.

**Operational Efficiency and Cost Reduction**: Through the mechanization of data documentation and validation processes, blockchain technology has the potential to mitigate manual tasks, diminish reliance on paperwork, and minimize human inaccuracies, thereby enhancing operational efficiency and lowering expenses related to error rectification, fraud oversight, and administrative functions.

**Challenges in Adoption**: Stakeholders must be prepared for organizational, technical, and legal challenges, including ensuring data integrity at input, managing resistance to information sharing, and addressing the need for skilled technical staff. [19]. A stage-by-stage implementation process and a clear understanding of consumer awareness are crucial

## VI. CONCLUSION

The rampant emergence of counterfeit pharmaceuticals constitutes a significant global dilemma, profoundly jeopardizing public health and the economic viability of the pharmaceutical sector. Conventional, disjointed supply chain frameworks lack the requisite transparency and traceability needed to effectively address this pervasive issue. The advent of blockchain technology, characterized by its fundamental principles of immutability, transparency, and decentralized consensus, presents a revolutionary approach to bolster the integrity and security of the pharmaceutical supply chain.

This scholarly article conducted an exhaustive comparative assessment of Hyperledger Fabric and private Ethereum, which are the two leading blockchain frameworks for enterprise utilization, grounded in extensive scholarly literature. The aims of this research were to evaluate these platforms against critical performance indicators, including security, scalability, privacy, and cost, and to ascertain their appropriateness for the management of drug supply chains.

Key findings demonstrate that Hyperledger Fabric consistently outperforms private Ethereum in "invoke" (write) operations, exhibiting significantly higher throughput and lower latency, which is crucial for recording the continuous flow of drug transactions and changes in custody. Its permissioned architecture and robust identity management further enhance data privacy and control, making it highly compatible with the strict regulatory and confidentiality requirements of the pharmaceutical sector. Conversely, private Ethereum excels in "query" (read) operations, offering faster data retrieval, but its performance for write-heavy workloads can be inconsistent due to gas fees and computational overhead.

Upon careful examination, it is posited that Hyperledger Fabric emerges as the most appropriate framework for implementation within the supply chain of the pharmaceutical sector. The platform's advantages in managing transaction-heavy, permissioned settings, in conjunction with its formidable security and privacy attributes, effectively respond to the sector's paramount requirements for credible traceability and the deterrence of counterfeiting. The trade-offs involve its limitations in concurrency for extremely high transaction volumes (beyond 1000 transactions) and slightly slower query performance compared to Ethereum for lower loads. Nevertheless, the integrity and speed of recording critical supply chain events outweigh these trade-offs for ensuring drug authenticity.

The implementation of Hyperledger Fabric would enable stakeholders to establish a transparent, tamper-proof, and efficient supply chain, fostering trust among all parties and ultimately safeguarding public health from the dangers of fake medications.

## VII. FUTURE WORK

The ongoing evolution of blockchain technology and its increasing adoption present numerous avenues for future research to further enhance its application in drug supply chain management:

**Explore integration with IoT, AI, or QR code tracking:** Further research should delve into how the combination of blockchain technology with IoT devices (for real-time environmental monitoring like temperature for cold chains), Artificial Intelligence (AI) (for predictive analytics on supply and demand, and fraud detection), and advanced QR code tracking systems can further enhance drug traceability and security. This includes empirical studies on how these integrated systems affect overall supply chain performance and decision-making.

**Expansion to other parts of healthcare supply chain:** Future research can explore the broader applicability of Hyperledger Fabric (or hybrid solutions) beyond drug traceability to other critical areas of the healthcare supply chain, such as medical device tracking, blood management systems, and electronic health records (EHR) management. This endeavor would necessitate an examination of particular use cases, regulatory frameworks, and the integration with pre-existing healthcare information technology systems.

**Adaptive Consensus Mechanisms**: Investigating the development and impact of adaptive consensus mechanisms or hybrid blockchain solutions that can address Fabric's concurrency limitations for extremely high transaction volumes while maintaining its core strengths.

**Interoperability and Standardization**: Further research is needed on developing common standards and interoperable architectures to link different blockchain systems at a global level, allowing for seamless information exchange across diverse pharmaceutical supply chains and regulatory bodies.

**Legal and Regulatory Frameworks:** Deeper research is required to address complex legal matters, conventional laws, jurisdiction, privacy, data sharing regulations, and intellectual property rights within a decentralised network, ensuring that blockchain solutions are not only technologically robust but also legally compliant

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