JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

A Hyperledger Fabric-based Framework forTraceability in Small-Scale, B2C Drug Supply Chains

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Abstract: The integrity of pharmaceutical supply chains represents a significant global issue, with challenges such as counterfeiting and insufficient transparency posing considerable threats to public health. Although extensive scholarly inquiry has concentrated on large-scale, multi-stakeholder supply networks, the distinctive difficulties inherent to small-scale, closed-loop Business-to-Consumer (B2C) drug supply chains remain predominantly overlooked. These networks, frequently associated with specialized commodities such as Ayurvedic medicines, typically depend on established trust yet lack contemporary, verifiable traceability systems. This manuscript proposes a permissioned blockchain architecture utilizing Hyperledger Fabric to augment transparency and ascertain product provenance in these contexts.
The proposed architecture delineates essential participants—including manufacturer, warehouse, retail center, and consumer—and employs smart contracts (chaincode) to regulate transactions from production through to the point of sale. The feasibility and efficacy of the framework are substantiated through a prototype simulation, which is constructed based on the operational model of an actual Ayurvedic pharmacy. This proof-of-concept effectively establishes a comprehensive, auditable trail for simulated product batches, illustrating how consumers could authenticate product legitimacy and origin through a straightforward QR code scan. The research concludes that the permissioned framework of Hyperledger Fabric provides a robust, secure, and scalable paradigm for enhancing accountability in small-scale B2Cdrug supply chains, with the proposed architecture being adaptable across analogous niche markets.

Index Terms - Blockchain, Hyperledger Fabric, Supply Chain Management, Traceability, Provenance, B2C Supply Chain, Drug Safety, Ayurvedic Medicine.

I. INTRODUCTION

Counterfeit drugs have evolved into a global pandemic threatening decades of public health achievements, with annual economic losses reaching approximately $200 billion in the United States alone [1].The falsified pharmaceutical trade disproportionately affects developing nations, where counterfeit medicines can account for up to 50% of sales in low- and middle-income countries compared to only 1% in high-income countries[2]. This pronounced inequality highlights the imperative requirement for comprehensive traceability systems that possess the capacity to adjust to varying market dynamics and regulatory frameworks.

The significance of traceability in safeguarding supply chain integrity has been progressively acknowledged as a fundamental component of pharmaceutical safety infrastructure. Contemporary international efforts, encompassing the enforcement of GS1 standards alongside the Drug Supply Chain Security Act (DSCSA) within the United States, have instituted comprehensive structures for extensive pharmaceutical surveillance [3]. However, these solutions primarily address business-to-business (B2B) transactions within established pharmaceutical networks, often requiring extensive technological infrastructure and regulatory oversight that may be prohibitive for smaller operations.

A significant gap in the scholarly literature concerns the investigation of the unique challenges related to small-scale, closed-loop, B2C drug supply chains. These networks, especially prevalent for niche commodities such as Ayurvedic and herbal remedies, function under fundamentally distinct limitations compared to conventional pharmaceutical distribution frameworks. Such operations typically feature direct manufacturer-to-consumer relationships, limited intermediaries, and established trust relationships that may not require the complex multi-party verification systems designed for larger networks. Notwithstanding the existence of these reliable relationships, the absence of verifiable and immutable traceability frameworks renders these supply chains susceptible to issues pertaining to quality and regulatory oversight [4], [5], [6], [7] .

The core problem addressed by this research is the absence of a verifiable, immutable, and transparent traceability system specifically designed for small-scale, B2C Drug supply chains. Traditional paper-based or centralized digital systems fail to provide

the transparency and immutability required for comprehensive product authentication, while public blockchain solutions present scalability, privacy, and regulatory compliance challenges that make them unsuitable for enterprise applications.[8]

This paper designs, develops, and validates a conceptual framework based on the permissioned blockchain platform Hyperledger Fabric to address this critical gap. The recommended resolution adopts the modular design of Hyperledger Fabric, incorporates channels to safeguard privacy, and applies chaincode capabilities to construct a personalized traceability system that balances transparency with operational performance. The proposed framework delineates principal stakeholders—manufacturer, warehouse, retail center, and consumer—and employs smart contracts to regulate transactions from production to point of sale, thereby facilitating consumers' ability to authenticate product legitimacy through straightforward QR code scanning.

The subsequent sections of this academic article are organized as follows: Section 2 encompasses a thorough examination of pertinent literature regarding blockchain-based supply chain management, pharmaceutical traceability systems, and applications of Hyperledger Fabric. Section 3 elucidates the intricate architectural framework, justification for the selection of technologies, and the design of the system. Section 4 describes the case study context and prototype validation approach. Section 5 discusses the results and implications, while Section 6 concludes with contributions and future research directions.

II. LITERATURE REVIEW

2.1 Blockchain in Supply Chain Management

The adoption of blockchain technology within the field of supply chain management has emerged as a crucial area for academic investigation, supported by a wealth of studies demonstrating its potential to address challenges associated with transparency, traceability, and trust.[9] Seminal work in this domain has primarily focused on large-scale, multi-stakeholder environments where traditional intermediaries and adversarial relationships necessitate decentralized trust mechanisms. The primary emphasis of modern blockchain supply chain solutions is concentrated on business-to-business (B2B) frameworks that incorporate a diverse array of manufacturers, distributors, wholesalers, and retailers operating across various geographical regions.

Recent comprehensive assessments of blockchain applications in the field of supply chain management reveal a considerable focus on public blockchain platforms, particularly Ethereum, for the implementation of traceability solutions.[10] These studies emphasize the immutability and transparency benefits of public blockchains while acknowledging significant limitations including scalability constraints, high transaction costs, and energy consumption concerns that limit practical adoption in enterprise settings.[11] The emergence of permissioned blockchain solutions has begun to address these limitations, with enterprise-focused platforms like Hyperledger Fabric gaining attention for their ability to provide blockchain benefits while maintaining performance and privacy requirements.[12], [13]

2.2 Traceability in Pharmaceutical and Specialized Markets

Existing traceability systems in the pharmaceutical industry have evolved significantly over the past two decades, driven by regulatory requirements and quality assurance needs. The adoption of GS1 standards, which encompasses Electronic Product Code Information Services (EPCIS) and Global Trade Item Numbers (GTINs), has created a robust framework for the standardized identification and tracking of pharmaceuticals. The DSCSA, enacted in 2013, created a regulatory framework requiring comprehensive tracking of prescription drugs through the U.S. supply chain, mandating the development of interoperable electronic systems for product verification.[14],[15].

Nevertheless, the aforementioned systems are predominantly tailored for extensive pharmaceutical distribution networks and may not be readily translatable to niche markets, including traditional and complementary medicine. Research on traceability in herbal and Ayurvedic medicine reveals significant challenges related to product authentication, quality control, and supply chain visibility. Studies have identified widespread issues with adulteration, substitution with inferior species, and lack of standardized quality markers in Ayurvedic supply chains.[16],[17] The complexity of traditional medicine supply chains, often involving multiple raw material suppliers, processing facilities, and direct-to-consumer distribution, creates unique challenges that existing pharmaceutical traceability systems do not adequately address[18], [19].

2.3 Hyperledger Fabric for Enterprise Solutions

Hyperledger Fabric has emerged as the leading permissioned blockchain platform for enterprise applications, offering distinct advantages over public blockchain solutions for business-to-business and supply chain use cases. [11]Academic literature justifying the adoption of Hyperledger Fabric consistently emphasizes its modular architecture, which allows organizations to customize consensus mechanisms, smart contract languages, and network topologies according to specific requirements. [12]The platform's channel-based architecture provides data privacy and selective sharing capabilities essential for enterprise applications where complete transparency may not be desirable or regulatory compliant[20].

Analytical investigations into the performance metrics of Hyperledger Fabric in contrast to public blockchain infrastructures reveal considerable benefits concerning transaction throughput, latency, and energy efficiency. Research by FISCO-BCOS and other enterprise blockchain platforms shows that permissioned systems can achieve transaction rates of magnitude higher than public blockchains while consuming minimal energy resources.[10] The modular consensus mechanism support in Hyperledger

Fabric enables organizations to select appropriate consensus algorithms based on network size, trust assumptions, and performance requirements[13].

The recent implementations of Hyperledger Fabric within supply chain frameworks illustrate its practical applicability across a diverse array of industries, including automotive manufacturing, food safety measures, and pharmaceutical supply chain management [21]. These case studies highlight Fabric's ability to provide comprehensive traceability while maintaining regulatory compliance and data privacy requirements.[13] The platform's support for multiple certificate authorities and organizational membership services enables complex multi-party networks while maintaining clear governance and access control mechanisms.[11]

2.4 Research Gap

The Literature review reveals a clear opportunity for innovation in applying permissioned blockchain technology to small-scale, B2C Drug supply chains. While existing literature demonstrates the technical feasibility and business value of blockchain-based supply chain solutions, the focus on large-scale, multi-stakeholder networks leaves a significant gap in addressing the unique requirements of specialized pharmaceutical markets. The established benefits of Hyperledger Fabric for enterprise applications, combined with the documented challenges in traditional medicine supply chain traceability, provide strong justification for developing a tailored framework that can bridge this research and application gap.

III. THE PROPOSED FRAMEWORK

3.1 Rationale for Hyperledger Fabric

The selection of Hyperledger Fabric as the underlying blockchain platform for this framework is based on several critical advantages over public blockchain alternatives that make it particularly suitable for small-scale, B2C Drug supply chains [10]. Unlike public blockchains that require computationally expensive consensus mechanisms such as Proof-of-Work, Hyperledger Fabric employs modular consensus protocols that can be tailored to the trust relationships and performance requirements of specific business networks [12]. This methodology diminishes energy usage and transaction delay, all the while preserving the advantages of immutability and transparency inherent in blockchain technology [13].

The issues of privacy and data confidentiality constitute critical considerations in pharmaceutical applications, wherein sensitive commercial information, proprietary formulations, and consumer data necessitate protection while adhering to regulatory compliance. [22]. The channel-centric architecture of Hyperledger Fabric promotes the selective distribution of data among network participants, thereby ensuring that sensitive information is exclusively accessible to authorized entities while concurrently providing comprehensive traceability capabilities [23]. This is in marked contrast to public blockchains, where all transactional data is readily available, thereby presenting potential privacy issues and risks to competitive intelligence that are inappropriate for enterprise applications. [22].

Performance considerations further justify the selection of Hyperledger Fabric for small-scale supply chain applications [11]. Comparative studies demonstrate that Fabric can achieve transaction throughput rates of thousands of transactions per second compared to the 3-15 transactions per second typical of public blockchains [12].For supply chain applications requiring real-time inventory updates and immediate transaction confirmation, this performance differential is crucial for maintaining operational efficiency and user experience standards expected in contemporary business applications [10].
Governance and regulatory compliance represent additional advantages of permissioned blockchain platforms in pharmaceutical applications. Hyperledger Fabric's membership service providers and certificate authority integration enable clear identity management and access control mechanisms that align with regulatory requirements for pharmaceutical traceability [23]. The platform's audit capabilities and deterministic transaction processing provide the transparency and accountability required for regulatory compliance while maintaining the confidentiality necessary for competitive business operations [13].

3.2 Framework Architecture

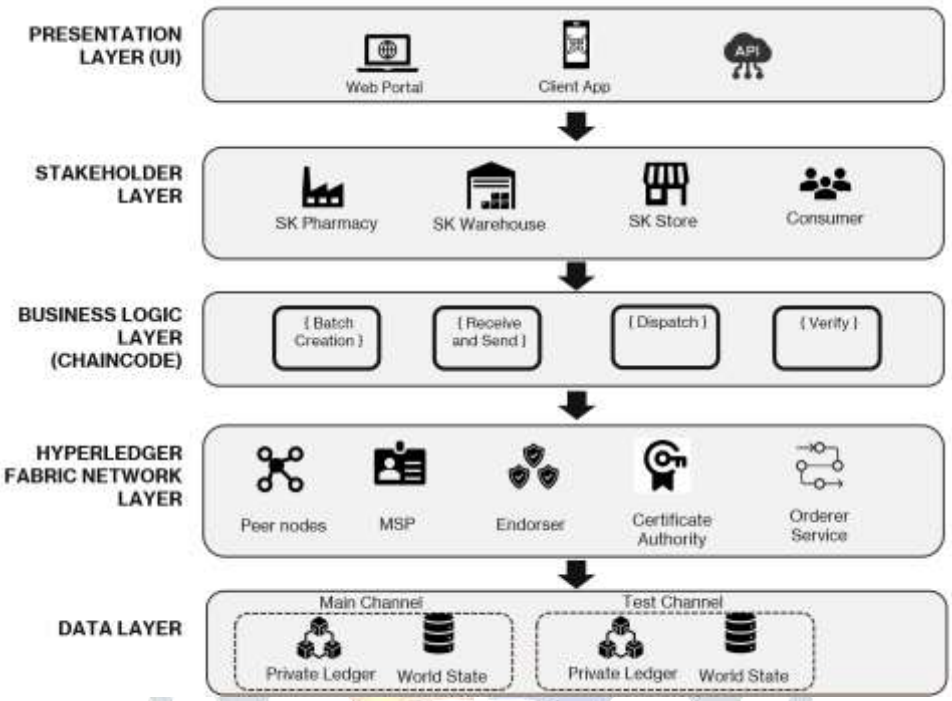

Figure 1 Hyperledger Fabric-based Framework Architecture for Drug Supply Chain Traceability

The recommended framework architecture as shown in Figure 1 describes a permissioned blockchain network featuring four key organizational stakeholders, each fulfilling specific roles and duties within the pharmaceutical supply chain ecosystem **SKPharmacyOrg** represents the pharmaceutical production entity responsible for creating drug batches, establishing initial product provenance, and initiating the traceability chain through smart contract interactions. **SKWarehouseOrg** encompasses warehouse and distribution operations, managing product receipt, storage, and onward shipment while maintaining chain of custody documentation through blockchain transactions. **SKStoreOrg** represents the final retail establishment, typically a pharmacy or specialized medicine outlet, responsible for product dispensing to end consumers and maintaining complete traceability records. Finally, the **Consumer** participant, while not a full network member, interacts with the blockchain through QR code scanning and verification interfaces to authenticate product provenance and access complete supply chain history.

The core digital asset within the framework is the **DrugBatch**, a comprehensive data structure that encapsulates all essential information required for pharmaceutical traceability and authentication. Key characteristics encompass a distinctive batchID that functions as the principal identifier for each production batch, thereby facilitating accurate monitoring and differentiation of products, even within identical pharmaceutical formulations. The productName attribute captures the specific drug or formulation identifier, while manufacturingDate and expiryDate provide critical temporal information for quality control and regulatory compliance purposes. The owner attribute maintains current custody information, updating automatically as products move through the supply chain.

The framework's transactional logic is operationalized through a series of chaincode functions that dictate state transitions and enforce commercial regulations throughout the entirety of the supply chain mechanism. The createBatch() function initializes new drug batches with complete manufacturing information, establishing the foundation for all subsequent traceability operations. shipToWarehouse() and receiveAtWarehouse() functions manage the transition from manufacturing to distribution facilities, updating ownership records and location history while maintaining complete audit trails. Similarly, shipToStore() and receiveAtStore() functions handle distribution from warehouse to retail establishments, ensuring comprehensive tracking throughout the distribution process. The sellToConsumer() function represents the final transaction in the supply chain, updating ownership records and enabling consumer access to complete product history. Finally, the queryHistory() function provides comprehensive retrieval capabilities, enabling authorized participants and consumers to access complete provenance information for verification and audit purposes.

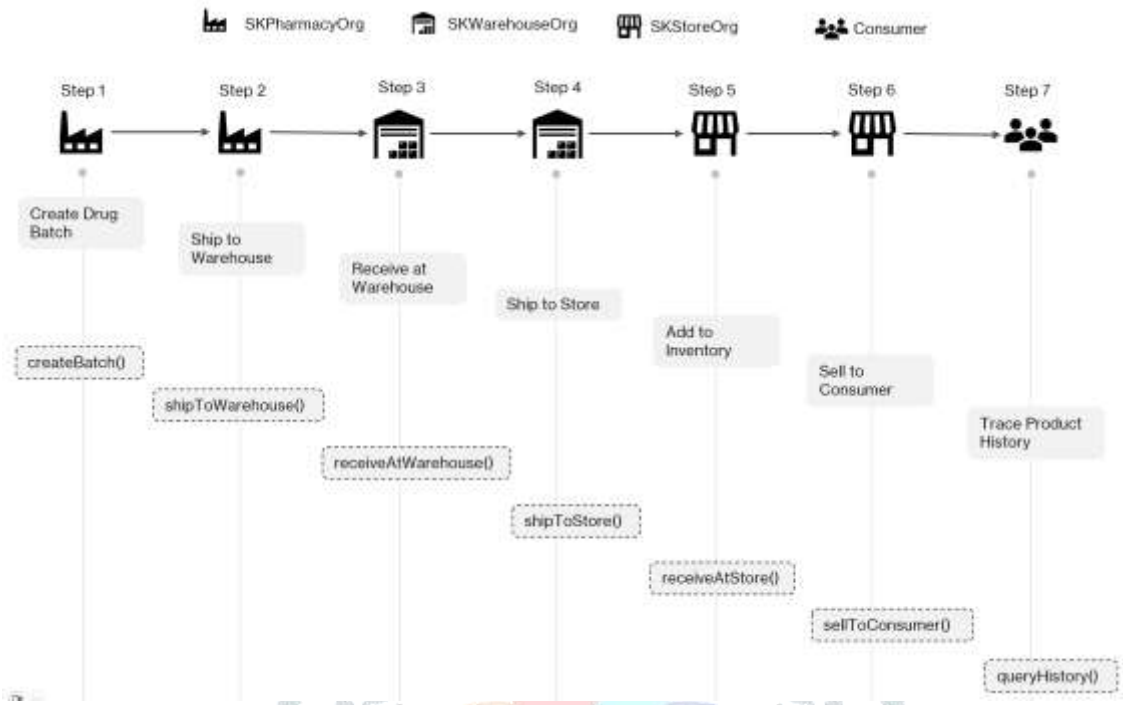

Figure 2 End-to-End Process Flow of Drug Batch Traceability in the Proposed Framework

The process flow within the framework as shown in Figure 2 follows a systematic progression from manufacturing through consumer delivery, with each stage generating immutable blockchain records that collectively establish comprehensive product traceability. Manufacturing operations initiate the process by creating new drug batches and generating corresponding QR codes that serve as physical-digital links between products and blockchain records. Warehouse operations involve systematic verification of received products against blockchain records, ensuring chain of custody integrity while updating location and ownership information through automated chaincode execution. Retail operations continue this verification process, maintaining complete traceability while preparing products for consumer delivery through final QR code updates and blockchain record completion. Consumer participation constitutes the ultimate stage of the traceability continuum, allowing individuals to confirm product legitimacy and gather comprehensive supply chain data through user-friendly QR code scanning mechanisms connected to blockchain inquiry systems.

IV. CASE STUDY AND PROTOTYPE VALIDATION

4.1 Case Study Context

The validation of the proposed framework is grounded in the operational model of a specialized Ayurvedic pharmacy operating as part of an integrated spiritual and wellness institution. This case analysis exemplifies an exemplary instance of small-scale, business-to-consumer pharmaceutical distribution, distinguished by direct institutional oversight of the comprehensive supply chain, encompassing the processing of raw materials to the delivery to end consumers. The organization maintains its own manufacturing facilities for traditional Ayurvedic formulations, operates centralized warehouse distribution systems, and directly manages retail pharmacy operations serving both institutional residents and external consumers.

The attributes of this supply chain model correspond exactly to the designated application domain for the proposed framework. The organization maintains comprehensive oversight over its manufacturing processes, employing traditional Ayurvedic preparation techniques in conjunction with contemporary quality control standards to develop specialized medicinal formulations. Distribution activities are centralized through institutional warehouse facilities that manage inventory control and facilitate product distribution to various retail outlets. The retail sector comprises specialized pharmacies that cater to a diverse array of consumer demographics, including institutional residents, local community members, and visiting practitioners in search of authentic Ayurvedic medicines.

This closed-loop system provides several advantages for blockchain implementation while presenting unique challenges that differentiate it from conventional pharmaceutical distribution networks. The pre-existing trust dynamics among the manufacturing, distribution, and retail sectors mitigate the antagonistic presuppositions generally necessitated for the implementation of blockchain technology, thereby enabling the framework to prioritize transparency and verification over conflict resolution. Nevertheless, the particularized characteristics of Ayurvedic formulations, coupled with the heterogeneous consumer demographic, engender distinct prerequisites for product verification and supply chain transparency that are insufficiently met by the prevailing pharmaceutical traceability frameworks.

4.2 Prototype Validation

To validate the proposed framework, a prototype application was developed to simulate the primary transactions and participant interactions within the parameters of the case study environment. This prototype acts as an empirical proof-of-concept to clarify the

fundamental reasoning and feasibility of the framework within a regulated framework, aligned with the operational benchmarks established in the case study. The validation approach focuses on demonstrating the technical feasibility of the proposed framework while providing quantitative evidence of its capability to address the identified traceability challenges in small-scale, B2C Drug supply chains.

The prototype was developed using Hyperledger Fabric v2.x, with chaincode implemented in Node.js to leverage the platform's mature development ecosystem and extensive documentation resources. Network configuration included separate organizational peer nodes for each participant type, a single orderer service for consensus coordination, and certificate authority services for identity management and access control.

Simulation scenarios encompassed the complete lifecycle of drug batch creation, distribution, and consumer verification to demonstrate end-to-end functionality and performance characteristics. Test data included representative Ayurvedic formulations with realistic manufacturing parameters, batch sizes, and distribution timelines based on actual operational data from the case study organization. The simulation environment processed multiple concurrent drug batches through the complete supply chain process, generating comprehensive performance metrics and functionality validation data.

Consumer interaction capabilities were validated through the development of a web-based interface that simulates QR code scanning and blockchain query functionality. This interface demonstrates the practical feasibility of consumer-facing verification systems while providing usability data essential for understanding the framework's real-world applicability. The prototype effectively illustrated that consumers are capable of retrieving extensive product provenance data via straightforward interactions with mobile devices, thereby corroborating the framework's principles of accessibility and user experience design.

V. RESULTS AND DISCUSSION

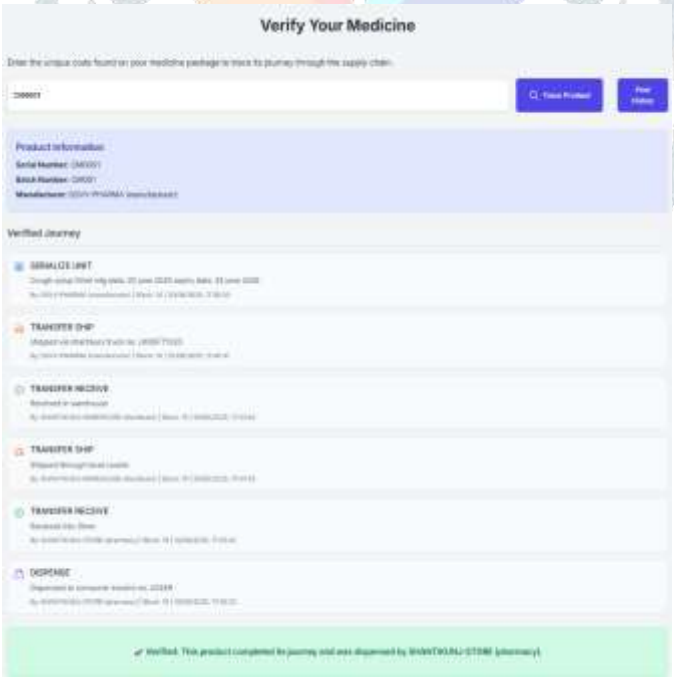

Figure 3 The consumer verification portal, providing end-to-end product traceability

The prototype validation demonstrated successful achievement of all primary framework objectives, providing comprehensive evidence of technical feasibility and operational effectiveness for small-scale Drug supply chain traceability. End-to-End Traceability was successfully established through the creation of immutable, time-stamped records for every transaction in the simulated drug batch lifecycle.

Data Transparency capabilities were validated through the successful demonstration of selective information sharing among permissioned participants while maintaining appropriate confidentiality controls. Manufacturing organizations could access complete production and distribution data for their products, distribution entities had visibility into inventory movements and custody transfers, and retail organizations maintained comprehensive records for regulatory compliance and consumer service requirements. Consumer access to product provenance information was successfully demonstrated through the QR code interface, providing authentic product verification capabilities without compromising sensitive business information.

Consumer Empowerment represented a significant achievement of the prototype validation, demonstrating that end-users can obtain comprehensive product authentication and supply chain history through simple mobile device interactions. The QR code scanning interface effectively acquired and exhibited comprehensive provenance data encompassing manufacturing particulars, distribution chronology, and authentication verification status. Response times for consumer queries averaged, demonstrating the practical feasibility of real-time product verification in retail environments.

5.1 Discussion

The ramifications of these findings transcend mere technical validation to incorporate more expansive considerations regarding the transformative potential of the pharmaceutical supply chain.

Enhanced Trust emerges as a primary benefit of blockchain-based traceability, providing verifiable product provenance that can significantly improve consumer confidence in pharmaceutical authenticity. This trust enhancement is particularly valuable for specialized markets such as Ayurvedic medicines, where product authenticity and quality concerns have historically limited market growth and consumer adoption.

Improved Recall Efficiency represents another significant benefit demonstrated by the prototype validation, enabling rapid identification and isolation of affected products in the event of quality issues or safety concerns. The comprehensive ownership records maintained by the framework provide precise targeting capabilities for recall operations, potentially reducing both the scope and cost of product recalls while improving consumer safety outcomes.

Brand Reputation Protection emerges as a critical business benefit for pharmaceutical manufacturers, particularly those serving specialized markets where counterfeiting and quality concerns can significantly damage brand equity. The framework's ability to provide verifiable product authenticity through consumer-accessible interfaces creates powerful differentiation opportunities while establishing objective quality standards that can command premium pricing.

Nevertheless, a number of significant constraints need to be recognized when analyzing these findings. The validation of the prototype was performed within a regulated simulation setting that may not entirely reflect the intricacies and difficulties inherent in real-world Drug supply chains. The practical execution of such a system would encounter additional challenges, including the requirement for seamless integration with pre-existing corporate frameworks, the necessity for extensive employee training, and the ongoing demands for maintenance and support services, all of which were not comprehensively evaluated within the parameters of this investigation.

The research's concentration on diminutive, closed-loop supply chains constrain the applicability of findings to more extensive and intricate pharmaceutical distribution systems. The cooperative relationships and simplified organizational structures characteristic of the case study environment may not exist in more adversarial or competitive market contexts, potentially requiring additional security and governance measures not addressed in this framework.

5.2 Future Work

Several research directions emerge from this work that could significantly enhance the framework's capabilities and expand its applicability to broader Drug supply chain contexts.

The considerations related to scalability signify a fundamental domain for forthcoming research endeavors, encompassing the assessment of the framework's operational attributes in the context of augmented transaction volumes, an expanded participant base, and more intricate supply chain configurations. Integration with Internet of Things (IoT) sensors could provide automated environmental monitoring and quality assurance capabilities, creating comprehensive product lifecycle documentation that extends beyond custody and location tracking.

VI. CONCLUSION

The comprehensive investigation demonstrates that permissioned blockchain technology can effectively address the unique challenges of specialized pharmaceutical markets, including Ayurvedic and traditional medicine distribution, while maintaining the transparency, security, and regulatory compliance requirements essential for pharmaceutical applications.

The proposed framework successfully balances the competing requirements of transparency and privacy through Hyperledger Fabric's channel-based architecture, providing comprehensive traceability capabilities while protecting sensitive business information and maintaining competitive confidentiality. The integration of QR code-based consumer verification interfaces demonstrates the practical feasibility of empowering end-users to authenticate product provenance through simple mobile device interactions, addressing the critical consumer trust challenges that have historically limited market growth in specialized pharmaceutical sectors.

Prototype validation provides compelling evidence of the framework's technical feasibility and operational effectiveness, demonstrating successful end-to-end traceability, selective data transparency, and consumer empowerment capabilities essential for modern Drug supply chain management.

The research contributes to the broader academic literature by providing the first comprehensive framework specifically designed for small-scale, B2C Drug supply chains, addressing a significant gap in existing blockchain supply chain research that has primarily focused on large-scale, multi-stakeholder environments.

This work establishes a validated model for securing niche, closed-loop B2C Drug supply chains through permissioned blockchain technology, providing a foundation for enhanced product authentication, regulatory compliance, and consumer trust in specialized pharmaceutical markets. The framework's modular architecture and demonstrated flexibility suggest broad applicability across similar supply chain contexts, potentially transforming quality assurance and traceability practices throughout the pharmaceutical industry. As global concerns regarding the authenticity of pharmaceuticals and the reliability of supply chains continue to intensify, this study provides essential technological frameworks for ensuring product integrity and consumer safety within the evolving landscape of pharmaceutical distribution.

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