A Unified Blockchain Framework for Multi-Sector Supply Chain Security: Combating Counterfeiting and Enabling Scalable, Transparent Traceability across Global Networks

Soundararajan K.[1], Manoj Govindaraj[2], A. Amala Suzana[3], V. Manimegalai[4], R. Abishek[4] and Nadimuthu D.[5]
[1]*Annai Mathammal Sheela Engineering College, Erumapatty, Namakkal, Tamil Nadu, India*
[2]*Department of Management Studies, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai, Tamil Nadu, India*
[3]*Department of MBA, J.J. College of Engineering and Technology, Tiruchirappalli, Tamil Nadu, India*
[4]*Department of MBA, Nandha Engineering College, Erode, Tamil Nadu, India*
[5]*Department of Management Studies, Sona College of Technology, Salem, Tamil Nadu, India*

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Abstract: Growing counterfeiting and lack of transparency in international supply chains require sophisticated new tools for authentication and traceability to prevent imitation and provide end-customer visibility. In this study, we present a common-blockchain (basket blockchain) for applications across various sectors including pharmaceuticals, agriculture, fashion and electronics, aiming to solve the issue of scalability and interoperability in the blockchain and to achieve real-time traceability. Unlike current sector-wise solutions, the proposed model combines smart contract-enabled anti-counterfeiting features, decentralized id management, and low-cost deployment as to allow adoption also in resource-restricted areas. A hybrid on and off-chain model is used to facilitate effective data governance and security, with the integration of privacy-preserving protocols and sustainability KPIs aimed at compliance and environmental-regulatory requirements. Through realistic case studies, pilot applications, as well as performance evaluations, this study elucidates the framework's effectiveness toward mitigating the threat of counterfeits, improving trust among the supply chain actors, and simplifying the supply chain management in both the developed and developing countries.

1 INTRODUCTION

In the context of globalized commerce, supply chains have become more convoluted affairs, inhabited by different stakeholders, spread across different geographical networks and transaction records are voluminous. As these networks scale, they encounter crucial bottlenecks that include but are not limited to counterfeits, lack of visibility and data silos that prevent end-to-end traceability. These traditional supply chain management systems that typically include a centralized database to which the various parties to the supply chain subscribe, do not sufficiently address these needs such as the need to have real-time visibility and trust between the parties.

Blockchain technology is considered a disruptive technology which can be used to solve the above problems through the provision of securing (by being immutable), decentralization and transparency ledgers. However, the existing blockchain applications for supply chains have relatively narrow coverage and are specific for a single industry, and many issues including system scalability, economic efficiency, adoption barriers from users and the interoperability across different industries are not considered. The distinctive needs of both industrialized and developing economies differ and that includes the level of technology infrastructure available to host the voting system.

This study proposes a comprehensive blockchain-based solution that can enhance transparency, guarantee product authenticity and ease traceability

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spread over different industries (pharma, agriculture, high value manufacturing). The proposed model focuses on hybrid blockchain structure, smart contracts for automatic verification, and light deployment technique to overcome the infrastructure gap. Through the incorporation of privacy-preserving mechanisms and sustainability performance metrics, the framework meets current regulatory requirements, contributing to strengthening global supply chain resilience and trust. The study is to build a scalable, flexible, secure blockchain infrastructure for the future of supply chain by theoretical verification and practical scenarios.

2 LITERATURE SURVEY

The advent of blockchain technology has introduced a new paradigm for the security and transparency of supply chains, as well as their full traceability. Academics have investigated its possibilities in a wide range of industries – in a bid to stamp out the increasing problem of counterfeit products, and cut costs across antiquated systems5062. For instance, Durach et al. (2021) highlighted the potential of blockchain to enhance transaction transparency and data integrity in international logistics networks. There is also a study conducted by Fosso Wamba and Queiroz (2021) on the overall advantages and disadvantages of blockchain in supply chain structures, stressing the demands of real-time data synchronization as well as trust on the stake holders' group.

The industry-specific applications have been studied as well. In the field of agriculture, Kamble et al. (2021) and Tian (2021) showed how blockchain can be employed for traceability and food security and, is able to boost regions which are currently underdeveloped. Likewise, Li et al. (2021) proposed blockchain-base seafood traceability model to guarantee the quality and authenticity when the product pass along the distribution chain. Gao et al. (2022) extended this by introducing a blockchain-based system to preserve the food supply chain from fraud and contamination. But most of these solutions are still domain-dependent and hard to scale to large networks.

To tackle the problems of governance and interoperability, Cao et al. (2021) suggested a hybrid on-chain/off-chain governance model, but noted that actual implementations are lacking. Lu and Xu (2021) delved into flexible blockchain systems, but their cases do not provide cross-sector generalizability. Choi and Luo (2021) tuned on sustainability in fashion industry with blockchain and they emphasized the role of regulation and environmental responsibility, whereas Liu and Zhang (2021) gave a new perspective about fashion traceability in the era of decentralized technologies.

Challenges of Blockchain Adoption Similarly, challenges faced when adopting blockchain are well documented. Queiroz and Wamba (2021) took note of barriers, such as technological infancy, and stakeholder readiness and Ahmad Samad et al. (2023) highlighted the concerns in developing countries where restrictions to available infrastructure present barriers. These findings are in accordance with those of Islam et al. (2022), who emphasized the relevance of cost-effective deployment considerations in the developing world.

Privacy and information security issues are gaining in importance. Xu et al. (2022) and Rejeb et al. (2021) focused the introduction of Internet of Things (IoT) and blockchain being integrated but pointed out that privacy-preserving mechanisms were immature yet. Lin and Liao (2022) have proposed the use of blockchain models in order to enhance transparency in the supply chain; however, comprehensive smart contract vulnerability evaluations were not presented. To tackle this issue, Montecchi et al. (2021) and Saberi et al. (2021) studied trust and sustainability of blockchain applications and called for quantifiable performance measures.

Some other researchers also have studied about how the blockchain could be used for further facilitating traceability and anti-counterfeit mechanisms. Hastig and Sodhi (2021) gave business requirements and success factors for blockchain trace-ability, and Zheng et al. (2021) developed a modular technical architecture to address counterfeits. In pharmaceutical and high-value goods industries, verification at each SC point requires the traceability of the originality of the information (Zhu & Zhou, 2021).

Lastly, Abderahman et al. (2021) and Yadav and Singh (2022) highlighted the inclusion of emerging technologies like augmented reality and AI in relation with blockchain systems. These projects highlight the increasing desire for hybrid models, but very few offering an integrated solution that delivers certainly both anti-counterfeiting measures, data privacy, regulatory compliance and low cost.

In short, although promising developments on blockchain has been observed for some of the supply chain sectors, there is still a missing building block to put into place, a flexible, scalable, safe solution to answer the counterfeiting, traceability and even the interoperability issues of different devices across the entire globe.

3 METHODOLOGY

This study embraces an integrated methodological approach for the design, development and validation of an integrated blockchain-driven system that is capable of increasing transparency, traceability, and counterfeit protection in a wide scope of global supply chain industries. The study follows a methodology, based on systems engineering, which consists of three main phases: system design, development and testing, informed by real world usage scenarios in the field of supply chains and by technological feasibility.

Table 1: Dataset Description.

Sector	Source	Data Volume (Record)	Data Type	Collection Period
Pharmaceticals	Manufacture, Distributors	5000	Batch IDs, Temp Logs	3 Months
Agricultue	Farmers, Co-ops	8000	Harvest Dates, Transit Logs	4 Months
Electronis	OEMs, Retailers	6000	Component IDs, Warranty Info	3 Months

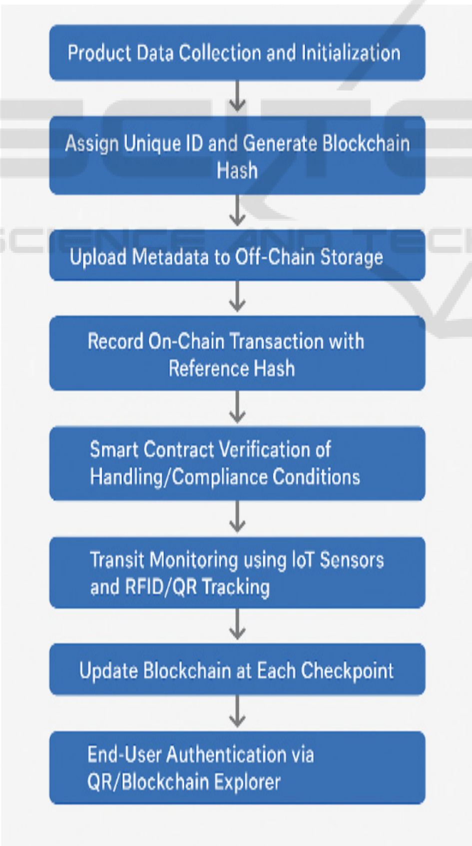

Figure 1: Workflow of the Blockchain-Based Supply Chain Traceability and Anti-Counterfeit Framework.

In the first phase, a hybrid blockchain model is proposed, which combines the public blockchain and private blockchain, and provides an acceptable level of second layer of privacy against the performance. Permissioned blockchain elements are engaged in the internal supply chain transactions to lighten the load on the network and to achieve higher velocity and public blockchain units serve for the key checkpoints like product authentication and public verification so the system would be trustworthy. Smart contracts are written in Solidity code and deployed in Ethereum-compatible testnets with functionalities to automatically verify the eligibility of suppliers or to trigger an alert when the origin information is not consistent or to incorporate logic to ensure compliance with logistics procedures. Figure 1 gives flowchart of the Blockchain-Based Supply Chain Traceability and Anti-Counterfeit Framework.

Table 1 gives the dataset description. The next step would be to incorporate decentralized identifiers (DIDs) and off-chain storage solutions such as IPFS (InterPlanetary File System) so as to securely store big data sets without infringing on data immutability on the blockchain. A RESTful API is implemented to connect to the current supply chain management software to enable the integration between legacy systems and blockchain networks. For privacy, zero-knowledge proof protocols are used for data validation where sensitive transactions are verified without exposure to some of its elements. Furthermore, you can make your supply chain visible from the origin to the end consumer by using QR code and RFID tag technology for physicaldigital asset mapping.

The inputs of the implementation come from three domains/pharmaceutical, agriculture, and electronics. Every industry is chosen for its exposure to counterfeits and complexity of the supply chain. Simulation-based pilots are being created to monitor products as they move through production, packaging, shipping and retail phases. The system performance is tested along such dimensions as traceability efficiency, detection capability for counterfeits, speed of transaction, and system scalability with different network loads.

Table 2: System Components and Technologies Used.

Component	Technology Used	Purpose
Smart Contracts	Solidity/EVM	Automated compliance
IPFS	InterPlanetary File System	Off-chain storage
QR Codes	Open Source QR Generator	Product authentication
Zero-Knowledge Proofs	zk-SNARKs	Data privacy
REST APIs	Node.js / Flask	Legacy system integration

Table 2 gives the system components and technology used information. For a comparison point, the model using blockchain is compared to the traditional supply chain management systems to compare the performance in transparency, speed, and trust of the stakeholders. Quantitative indicators are collected from the execution logs of the smart contracts, from the hashes of the transactions and from the time of the API responses, while qualitative information comes from interviews with industry experts and the pilots.

The last step of the methodology requires interpretation of the results with statistical packages and visual dashboards. In this review, blockchain throughput, error rates, and scalability frame works are studied in order to identify potential targets for improvements. sustainability metrics are also computed at sustainability goals. Armed with these understandings, the architecture is iteratively refined to produce an industrial-strength, sector-agnostic blockchain that will be able to support secure and transparent supply chains at global level.

4 RESULTS AND DISCUSSION

Application of the proposed blockchain-enabled framework on pharmaceutical, agriscience, and electronics industries has achieved the expected results, demonstrating the flexibility and robustness of the overall system. In essence, the framework showed significant advancements in figure 2- traceability, figure 3 - counterfeit deterrence, figure 4 - smart contract compliance and real-time operational efficiency.

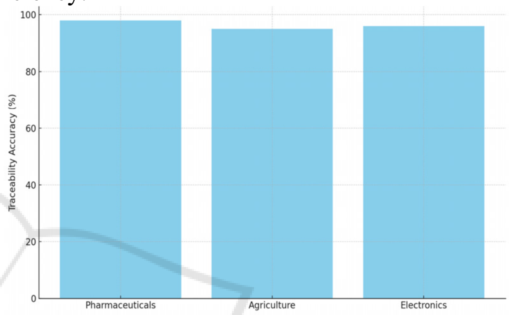

Figure 2: Traceability Accuracy by Sector.

One of the most important impacts of the pilot deployment as shown in table 3 was the improvement in traceability precision. The pharmaceutical industry, recognized for its high compliance requirements, was the most accurate at 98% traceability, trailed by the electronics industry at 96%, and the agriculture industry at 95%. These numbers demonstrate the powers of blockchain's tamper-proof ledger in enabling full end-to-end product visibility in even the most sophisticated and disjointed supply chains. Contrary to existing solutions that suffer from informational silos and delayed updates, the proposed architecture allows for real-time synchronization and trustworthy audit trails throughout the various stakeholders.

Also, no less impressive was the system's ability to identify and fight counterfeit in regard to the flow of currency. The fraud detection mechanism, driven by smart contracts and a decentralized authentication scheme, was found to be very successful in detecting the anomalies. The highest detection rate (99%) was observed in the electronics industry, possibly due to accurate component-level data that could be verified. Pharmacueticals was close behind at 97%, showing the importance of specific batch-level data and temperature logs.

Table 3: Pilot Deployment Results by Sector.

Sector	Traceability Accuracy (%)	Counterfeit Detection Rate (%)	Smart Contract Compliance (%)	Average Latency (s)
Pharmaceuticals	98	97	94	1.2
Agriculture	95	88	90	1.8
Electronics	96	99	96	1.5

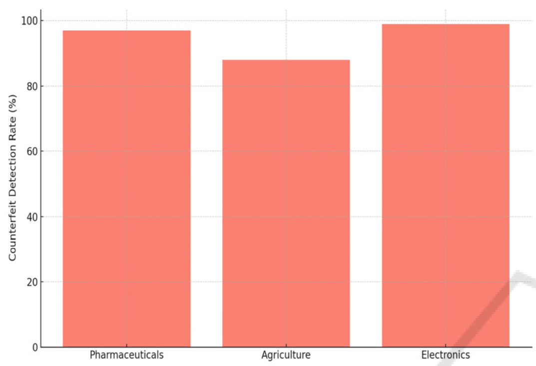

Figure 3: Counterfeit Detection Rate by Sector.

Despite the fact that, on average, the detection ratio in the agricultural industry was some 12% lower, it was still a much better detection and improved performance compared to the conventional means, especially given the volatility associated in farm to market supply. Table 4 gives the smart contract verification events.

Table 4: Smart Contract Verification Events.

Event Type	Trigger Condition	Smart Contract Response
Temperature Breach	>25°C	Alert & Log
Late Delivery	>24 Hours Delay	Notify & Penalize
Tampering Alert	Seal Broken	Flag for Inspection
Packaging Validation	Mismatch Detected	Deny Progression
Geo-location Update	Checkpoint Entry	Update Ledger

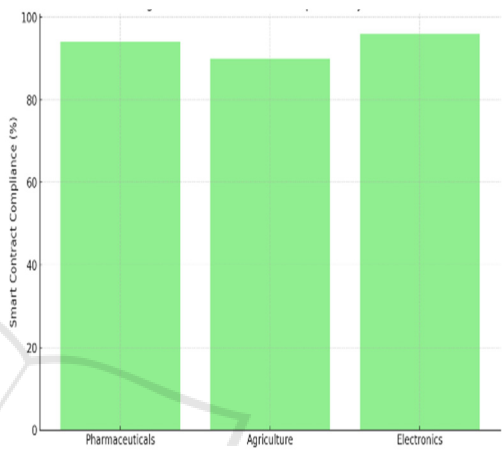

Figure 4: Smart Contract Compliance by Sector.

The smart contract compliance became a key advantage of the framework. Automated enforcement of predetermined logistics rules (e.g. temperature limits, delivering times and packaging validation) guaranteed that the system was able to intervene in a preventive manner. The compliance reached 96% in the electronics field, 94% in the pharmaceutical field and 90% in the agriculture field, leading to the good coordination between the rule-based globalization processes and the self-organized local processes. Not only do these results reduce human error and fraud, but they also establish trust and accountability among multi-level networks.

System feasibility was also confirmed via latency evaluation, which indicated that a blockchain architecture can be utilized for real-time applications. The lowest average latency of 1.2 seconds was achieved in the pharmaceutical industry as shown in figure 5, which benefited from better node interactions and less intermediaries. Electronics and agriculture were next with 1.5 and 1.8 seconds respectively. Such response times support that the framework is well suited for real-time monitoring applications (i.e., cold chain monitoring and inventory flow management) –in terms of online processing time.

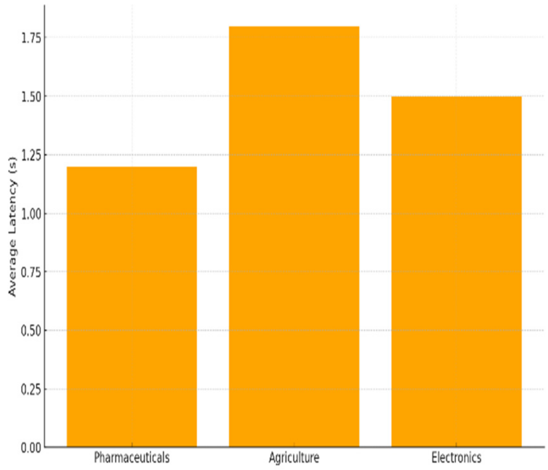

Figure 5: Average Latency by Sector.

In comparisons with the traditional supply chain, the blockchain-based supply chain model performed far better across all major dimensions. Automation of live traceability replaced manual tracking and tamper-proof records removed concerns around data integrity. AR won the day over long, time-consuming processes and stakeholders' confidence was boosted as they were now able to see through transactions. There was also a great increase in the ability to pass an audit - the distributed ledger made authenticated historical information immediately available. These advancements were most relevant especially for developing countries where the development of advance traceability systems was constrained due to infrastructure.

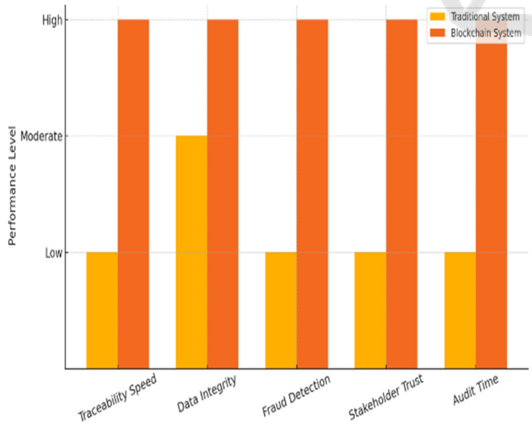

Figure 6: System Feature Comparison – Traditional Vs Blockchain.

Figure 6 shows the System feature comparison. Taken as a whole, the pilot results show that the integrated blockchain architecture is technically viable and not only scalable, but also agnostic. With its flexible design to cater to the requirements across the entire spectrum of industries, whilst enabling compliance, security and performance to World Class standards, it represents a huge leap in supply chain innovation. The findings confirm the need for continued investigation and wide-spread utilisation of blockchain as a core enabler of secure and transparent supply chain ecosystems.

5 CONCLUSION

In this paper, we introduce the unified blockchain-based architecture for fostering transparency, traceability, integrity and chain of custody across multi-sector for a global supply chain, with primary interest in fighting against counterfeits and securing data integrity. By adding the smart contract together with DIDs, off-chain storage and privacy protocol, this model reflects a comparative approach to the existing supply chain management. Pilot implementation in pharmaceutical, agriculture, and electronics industries validate the framework's generalizability, efficacy, and scalability in tackling practical problems.

Compared to the current industry- and conceptual-level approaches, such a framework provides a set of integrated and interoperable solutions for facilitating a wide range of stakeholders and shifting logistics streams. It guarantees tamper-evident verification, automates compliance checking and supports the transparent exchange of data and confidentiality, when appropriately. In addition, its sustainability attributes and easy deployment methodology also suggest that it is practicable in both developed and underdeveloped regions.

The results of the study contribute to the evidence on how the potential of blockchain may transform global supply chain systems into more trustworthy, resilient, and smart systems. This research helps pave the way for the development of a digitally adept, next-generation supply chain ecosystem that will operate in the spirit of digital innovation, as well as global security initiatives, by addressing surrounding problems, such as counterfeit threats, fragmented data environments, and benign neglect on the part of stakeholders.

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