

Article

Blockchain-Based Traceability and Age Verification for Nicotine Products

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Abstract

Underage access to nicotine products and the circulation of counterfeit tobacco remain significant public health and regulatory challenges, largely driven by limited supply-chain visibility, centralized record manipulation, and weak enforcement of age-restriction policies. Many existing digital monitoring systems lack immutability and fail to integrate regulatory controls directly into transaction execution. This study proposes a blockchain-based traceability and age-verification framework for nicotine products that ensures end-to-end transparency while enforcing compliance through smart contracts. The system employs a permissioned blockchain to generate immutable records of product movement from manufacturing to retail and embeds age-verification logic linked to national identity credentials within transaction authorization. A mobile application interfaces with the blockchain to enable real-time product authentication and compliance verification at the point of sale. The framework was evaluated using simulated retail and regulatory inspection scenarios, focusing on traceability completeness, enforcement accuracy, transaction latency, and throughput. Experimental results demonstrate effective prevention of underage purchase attempts, tamper-resistant provenance tracking, and consistently low transaction latency suitable for real-time retail operations. Overall, the findings indicate that smart-contract-enforced blockchain traceability provides a practical and reliable approach for strengthening regulatory compliance, combating counterfeit nicotine products, and protecting public health.

Keywords: blockchain-based traceability; regulatory compliance; permissioned blockchain; smart contracts; age-restricted products; product authentication; supply-chain provenance; tamper-resistant records

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1. Introduction

Digital enforcement and inventory management systems currently used to regulate nicotine products remain insufficient to prevent underage access and the

circulation of counterfeit goods. Most existing solutions rely on centralized databases, manual verification procedures, and fragmented audit mechanisms, which expose them to record tampering, retroactive modification, and inconsistent enforcement at the point of sale [1]. In

such centralized architectures, product movement data and verification logs are typically controlled by individual stakeholders, which limits cross-organizational transparency and weakens regulatory oversight. Furthermore, privacy and security vulnerabilities associated with centralized data repositories reduce trust, particularly when sensitive identity and transaction information is involved [2]. These limitations point to the need for a trustworthy, verifiable, and automation-driven enforcement framework that supports regulatory compliance throughout the entire nicotine product supply chain.

Nicotine consumption among adolescents continues to pose a serious public health concern, particularly with the increasing shift from conventional cigarette smoking to electronic cigarettes and vaping products. In Malaysia, the National Health and Morbidity Survey (NHMS) 2022 reports a decline in cigarette smoking among adolescents aged 13–17 years from 13.8% in 2017 to 6.2% in 2022. However, this positive trend is offset by a substantial increase in e-cigarette and vape usage, which rose from 9.8% to 14.9% during the same period [3]. This pattern shows that young people are changing how they use nicotine, not that they are getting less of it overall. Accessibility through commercial retail channels remains a significant contributing factor, as empirical evidence shows that a considerable proportion of adolescents obtain nicotine products directly from retail outlets, particularly in urban environments [4].

The persistence of illicit and counterfeit nicotine products further exacerbates these challenges. Unregulated products often bypass formal supply chains, tax controls, and age-verification mechanisms, thereby undermining national tobacco control strategies and weakening the effectiveness of enforcement [5]. Despite the implementation of excise taxes, statutory age restrictions, and public health awareness campaigns, underage access and illicit distribution remain prevalent, indicating structural limitations in existing regulatory approaches [6]. These observations suggest that policy and surveillance measures alone are insufficient without complementary technological mechanisms capable of enforcing compliance at the transaction level.

To address these gaps, regulatory systems must ensure both end-to-end supply-chain traceability and reliable age verification that cannot be selectively applied or bypassed. Blockchain technology has emerged as a promising foundation for such systems due to its decentralized architecture, immutability, and ability to

provide verifiable audit trails across multiple stakeholders. Unlike conventional digital systems that primarily support retrospective monitoring, blockchain-enabled smart contracts enable enforcement logic to be embedded directly within transaction workflows, thereby shifting compliance from post-hoc verification to real-time execution control.

In response, this study proposes a blockchain-based traceability and age-verification system for nicotine products that integrates immutable product provenance with identity-aware enforcement mechanisms. The proposed architecture ensures comprehensive tracking of nicotine products from manufacturing to retail while incorporating secure age verification using National Identification Card credentials at the point of sale. By leveraging smart contracts on a permissioned blockchain, age-restriction policies are enforced as mandatory conditions during transaction execution, preventing non-compliant sales from being completed or recorded. This integration of product authentication, identity verification, and automated enforcement aims to strengthen regulatory compliance, reduce counterfeit circulation, and support public health objectives by more effectively preventing underage access to nicotine products [7].

The main contributions of this study are threefold. First, it presents a permissioned blockchain architecture that unifies product traceability and age-restriction enforcement within a single transaction workflow. Second, it introduces a smart-contract-based authorization mechanism that enforces age verification at execution time rather than relying on post-hoc audits or discretionary retailer checks. Third, it provides an experimental evaluation of the proposed system, demonstrating its functional correctness and performance feasibility for real-time retail environments in terms of transaction latency and throughput.

2. Related work

This section reviews prior research and existing systems relevant to blockchain-based traceability, regulatory enforcement, and age-restricted nicotine products. The discussion is organized first to examine blockchain-enabled supply-chain traceability, followed by public health and regulatory challenges related to youth nicotine consumption, enterprise blockchain and data-sharing technologies, commercial traceability platforms, and academic prototype systems. This structured review highlights the limitations of existing approaches and establishes the research gap that the proposed system addresses.

2.1 Blockchain-Based Supply-Chain Traceability

Blockchain technology has been extensively explored as a mechanism for improving transparency, integrity, and trust in supply chain management. Prior studies demonstrate that blockchain-based systems provide immutable and transparent records, tamper resistance, and verifiable audit trails that significantly outperform conventional centralized databases, particularly in logistics-intensive and compliance-critical environments [8]. These characteristics are especially relevant for regulated product supply chains, where accountability across manufacturers, distributors, and retailers is essential for effective monitoring and enforcement.

2.2 Youth Nicotine Consumption and Regulatory Challenges

Beyond technical considerations, public-health research highlights persistent challenges in controlling youth access to nicotine products. Studies report strong adolescent interest in flavored e-cigarettes, which increases experimentation and early initiation of nicotine use [9]. Recent surveillance data further confirm continued usage of e-cigarettes and nicotine pouches among middle- and high-school students, indicating that youth exposure remains substantial despite regulatory efforts [10]. Global health authorities have identified illicit marketing practices and unregulated supply chains as significant youth enablers access, allowing nicotine products to bypass age-verification controls and safety regulations [11]. These findings demonstrate the importance of enforcement mechanisms that operate directly at the point of sale rather than relying solely on post-hoc monitoring.

2.3 Enterprise Blockchain and Secure Data Sharing

Enterprise blockchain platforms have been evaluated for their applicability in regulated environments, with comparative analyses examining systems such as Hyperledger Fabric, Quorum, Corda, and Ethereum. These studies highlight necessary trade-offs in governance, scalability, transaction latency, and deployment complexity that directly affect suitability for regulatory enforcement applications [12]. Complementary research on interoperable and secure data-sharing architectures further emphasizes the importance of protecting sensitive information while maintaining verifiability, particularly when identity or health-related data are involved [13].

In the context of tobacco control, traceability systems incorporating technologies such as Global Positioning Technology (GPS) and Radio Frequency Identification (RFID) have demonstrated improvements in product monitoring and logistics transparency. However, the

solutions typically remain dependent on centralized control points and do not directly embed age-restriction enforcement into transaction execution, thereby limiting their effectiveness in preventing underage sales [14].

2.4 Privacy-Preserving Blockchain Architectures

To address privacy concerns, several blockchain-based data-sharing frameworks propose hybrid on-chain and off-chain architectures. These designs store sensitive data off-chain while maintaining cryptographic proofs, access control, and auditability on-chain, enabling secure and privacy-preserving verification processes [15]. Such approaches are particularly relevant for age-restricted retail systems, where enforcement must be verifiable without exposing personal identity data unnecessarily.

2.5 Commercial Traceability and Identity Platforms

Several commercial platforms have leveraged blockchain and digital identity technologies for purposes of traceability and verification. ReCheck.io focuses on digital product verification and authentication workflows [16], VeChain [17] emphasizes end-to-end supply-chain transparency across logistics ecosystems, and Civic [18] provides decentralized identity solutions for secure user verification. While these platforms demonstrate real-world feasibility, most offer partial solutions in regulatory contexts, as traceability and identity verification are often decoupled, and age-restriction enforcement is not enforced as a mandatory transaction constraint.

2.6 Academic Prototypes and Research Gaps

Academic prototype systems have explored blockchain architectures for secure information sharing and distributed governance across multi-party environments. However, many proposed solutions focus on general-purpose data exchange rather than enforcement-sensitive retail scenarios. Several designs rely on public blockchain infrastructures, introducing higher transaction costs and latency, or hybrid architectures where critical enforcement logic remains centralized, reducing accountability and auditability [19], [20]. Security-focused studies further highlight unresolved risks such as identity spoofing, replay attacks, and enforcement bypasses when policy controls are not cryptographically bound to transaction execution [21].

In contrast to existing commercial platforms and academic prototypes, the proposed system integrates immutable product traceability, identity-aware age verification, and smart contract-based transaction authorization within a unified, permissioned blockchain workflow. By enforcing age-restriction policies directly at

execution time while maintaining low-latency performance and verifiable audit trails, the proposed approach addresses key limitations identified in prior work and provides a practical, enforcement-ready solution for regulated nicotine-product supply chains.

3. Methodology

This study adopts an iterative and modular system development methodology to design, implement, and evaluate a blockchain-based traceability and age-verification platform for regulated nicotine products. An Agile-oriented development approach was selected to support incremental implementation, continuous testing, and systematic refinement of system components. This methodology is particularly suitable for systems that integrate heterogeneous technologies—such as mobile applications, blockchain smart contracts, and off-chain data storage—where early validation of individual modules reduces integration risk and improves overall system reliability.

The development process was organized into short iterations, each focusing on a distinct functional capability, including product registration, age verification, transaction authorization, and record retrieval. Functional testing was conducted at the end of each iteration to verify correctness and alignment with regulatory requirements. This incremental approach enabled early identification of design constraints related to blockchain interaction latency, transaction validation logic, and user workflow usability before full system integration.

3.1 System Architecture Design

The proposed system employs a hybrid architecture that integrates decentralized blockchain components with conventional off-chain storage, thereby balancing transparency, security, and operational efficiency. A permissioned blockchain model was selected to satisfy regulatory governance requirements, ensure predictable transaction latency, and avoid transaction fees associated with public blockchain networks. This design aligns with regulator-led or consortium-based deployment models commonly required in compliance-sensitive environments.

As illustrated in Figure 1, the system consists of four primary layers: (1) the mobile application layer, (2) the application middleware layer, (3) the blockchain enforcement layer, and (4) the off-chain data storage layer.

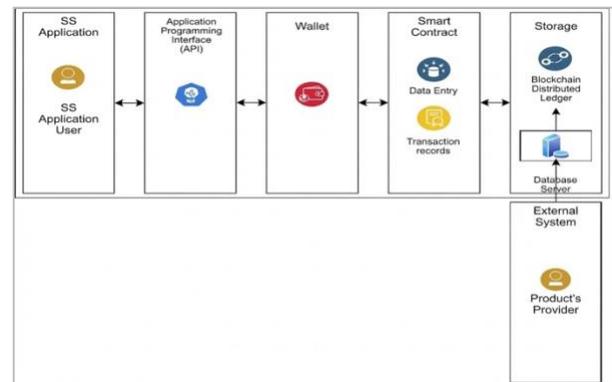


Figure 1. Architecture of the proposed blockchain-based traceability and age-verification system

The user interface for the application is implemented using React Native, providing a cross-platform mobile interface for retailers and inspectors. This interface supports product verification, customer age validation, transaction confirmation, and viewing audit records. The application middleware is built with Node.js and Express.js, which provides APIs to manage transaction requests, connect with the blockchain, and handle data operations that are not on the blockchain.

The blockchain layer is implemented using Solidity-based smart contracts deployed on an Ethereum platform within a permissioned blockchain environment, utilizing Ganache. Smart contracts are responsible for enforcing regulatory compliance logic, including validation of product authenticity, verification of customer age eligibility, and authorization of sales transactions. Interaction between the application layer and the blockchain is managed using Ethers.js, which handles wallet integration, transaction signing, and smart contract invocation.

Off-chain data storage is implemented using SQLite, which stores supplementary product metadata, user interface state data, and non-sensitive operational records. This hybrid design ensures that critical enforcement decisions and transaction proofs remain immutable and tamper-resistant on-chain, while auxiliary data are managed off-chain to improve query efficiency and system responsiveness.

3.2 Transaction Workflow and Enforcement Logic

The transaction workflow begins at the point of sale when a retailer initiates a product transaction through the mobile application. The system first validates the product identifier against registered on-chain records to confirm authenticity and provenance. This step prevents counterfeit or unregistered products from entering the retail workflow.

Following successful product authentication, the system initiates mandatory age verification. The retailer inputs the customer's National Identification Card number, which is used to determine age eligibility. Age verification is enforced as a precondition for transaction execution, meaning that transactions involving underage customers are rejected at the smart contract level and are neither executed nor recorded on the blockchain.

Once all compliance conditions are satisfied, the retailer is presented with a consolidated transaction summary for final confirmation. Upon confirmation, the transaction is cryptographically signed and submitted to the blockchain network. The smart contract validates the transaction parameters and, if authorized, records an immutable transaction entry on the blockchain ledger. Simultaneously, the transaction details are stored in the off-chain database for operational and reporting purposes.

This workflow ensures that regulatory enforcement is embedded directly into transaction execution rather than relying on post-hoc audits or discretionary retailer actions. The resulting blockchain ledger provides a verifiable audit trail that supports compliance monitoring, inspection, and investigation.

3.3 Implementation Assumptions and Scope

The current implementation assumes the trusted onboarding of manufacturers and retailers into the permissioned blockchain network. Customer input is treated as untrusted until validated through the age-verification mechanism enforced by smart contracts. The prototype focuses on enforcing age restrictions and product authenticity, but does not address advanced adversarial scenarios, such as compromised retailer devices, large-scale insider collusion, or denial-of-service attacks.

All system evaluations were conducted in a controlled experimental environment using a local blockchain network. While this setup enables precise measurement of functional correctness and baseline performance, it does not fully capture the network conditions or governance complexities of a production-scale deployment.

4. Results

4.1 Technical Integration and Blockchain Connectivity

The implementation phase successfully established functional connectivity between the mobile application and the blockchain network through the integration of Ethers.js. This middleware enabled the application to interact with deployed smart contracts, supporting

transaction signing, submission, and retrieval of validation outcomes. The terminal output shown in Figure 2 confirms the successful invocation of the smart contract, including transaction execution and the creation of an on-chain record.

These results verify the correct serialization of transaction data and successful communication between the application layer and the Ethereum-compatible blockchain environment used in the experimental setup. The observed interactions confirm that the application can reliably submit transactions to the smart contract and receive execution feedback in real time.



```

Deserializing fetched cigarette: {
  id: 1,
  name: 'Marlboro Red',
  factory: 'Philip Morris International',
  manufacturedDate: 2025-04-27T07:18:34.000Z
}
Verifying age... IC: 828527058177 name Izzat
Customer age is 23
Creating record in blockchain...
Finish transaction for creating record
Requesting all records from smart contract located at: 0x6Ae1506e499bF57743837eFC01da6637Ec52998
Fetching records from smart contract located at: 0x6Ae1506e499bF57743837eFC01da6637Ec52998
Fetching cigarette id 1
  
```

Figure 2. Terminal output confirming successful smart contract interaction and blockchain connectivity

4.2 System Output and Functional Workflow

The system output demonstrates the complete operational workflow designed to support product authentication and age-restriction enforcement. The process begins when a retailer enters a cigarette product identifier through the mobile application. As shown in Figure 3a, the system queries registered records and verifies whether the product exists within the recorded supply-chain data. Upon successful validation, the application confirms product authenticity and retrieves associated metadata, including the product identifier and origin information.

Following product authentication, the system enforces mandatory age verification. The age-verification interface is presented in Figure 3b, where the retailer inputs the customer's National Identity Card number. The system evaluates age eligibility before allowing further action. If the age requirement is satisfied, the transaction workflow proceeds. If the customer does not meet the legal age requirement, the transaction is rejected and cannot be executed, thereby enforcing compliance at the point of execution.

After successful age verification, the system presents a consolidated transaction summary for final confirmation, as illustrated in Figure 4a. This summary displays the relevant product and transaction details, enabling the

retailer to review the information before submission. Once confirmed, the transaction is executed through the smart contract and recorded on the blockchain ledger, while supplementary data is stored in the local database.

All completed transactions are accessible through the records interface shown in Figure 4b, which provides a chronological view of verified sales along with corresponding blockchain transaction references. This interface supports transparent review and audit of historical transactions, facilitating traceability and compliance monitoring.

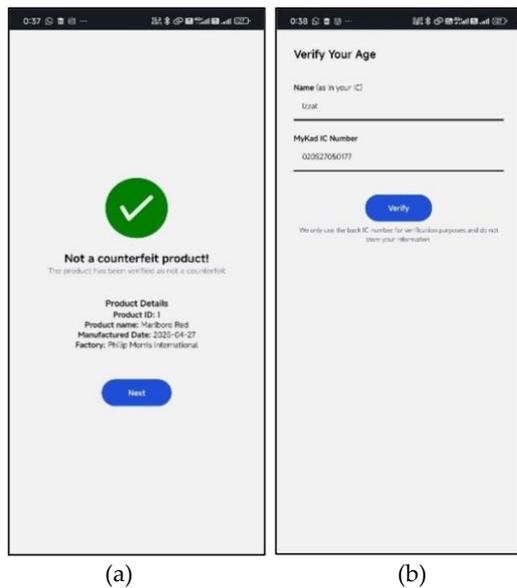


Figure 3. System validation workflow (a) Product authentication result (b) Customer age verification interface

4.3 System Testing

User acceptance testing was conducted to evaluate the functional accuracy and basic usability of the application under simulated retail conditions. A small focus group interacted with the system by performing tasks such as product verification, age validation, and transaction recording. Across all test sessions, the system consistently enforced age restrictions and recorded authorized transactions as intended.

Participant feedback indicated that the application workflow was understandable and aligned with typical retail interaction patterns. No functional errors affecting transaction execution or record retrieval were observed during the testing process. These results indicate that the implemented workflow operates correctly within the defined experimental scope.

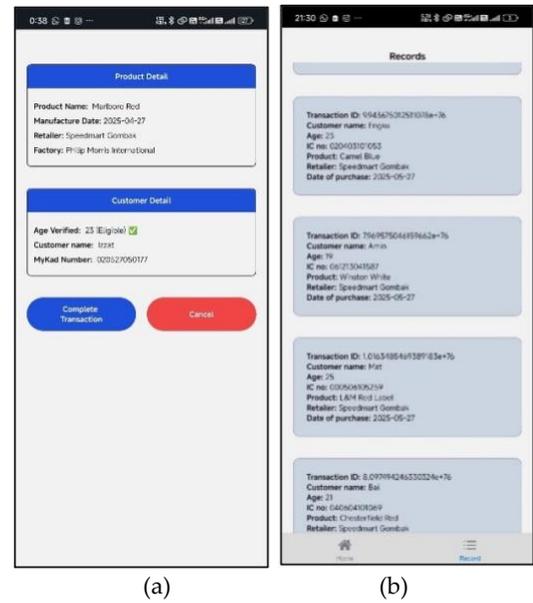


Figure 4. Transaction completion and audit view (a) Transaction summary before confirmation (b) Recorded transaction history

4.4 Performance Analysis

The performance evaluation focuses on transaction latency and throughput behavior under varying transaction loads. Figure 5 presents the average transaction latency observed across multiple execution trials. The results indicate consistently low latency with limited variance across trials, suggesting that smart contract execution and on-chain validation introduce manageable processing delays within the experimental environment. These latency characteristics are compatible with real-time point-of-sale interaction under controlled conditions.

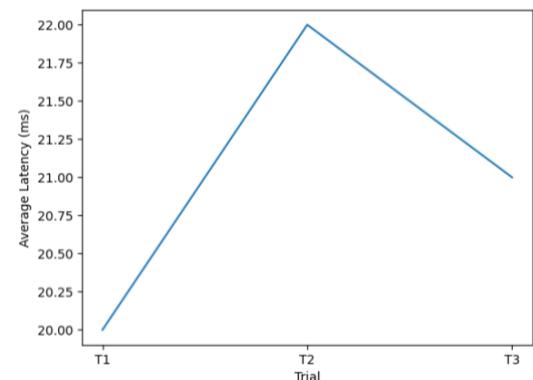


Figure 5. Average transaction latency per execution trial

System throughput under increasing transaction load is illustrated in Figure 6. The results show that throughput increases steadily under light and moderate loads before stabilizing as transaction volume increases. As load increases, latency also rises; however, the system continues

to operate predictably without transaction failure, indicating controlled performance degradation rather than instability.

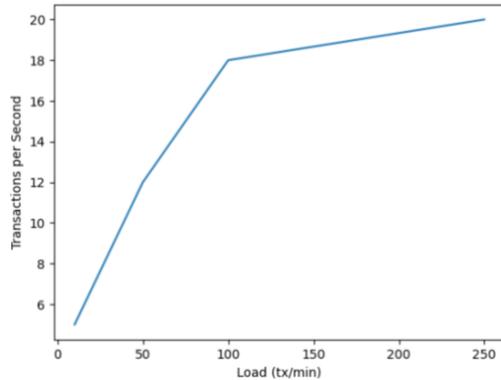


Figure 6. System throughput under increasing transaction load

Table 1 summarizes the minimum, average, and maximum transaction latency observed across trials. The results confirm consistent processing times without extreme spikes, supporting the reliability of retail usability.

Table 1. Transaction latency analysis

Trial	Min (ms)	Avg (ms)	Max (ms)
T1	10	20	35
T2	12	22	38
T3	11	21	36

Table 2 presents the throughput performance under increasing transaction load. The system maintains stable performance under lower loads and exhibits gradual degradation as the load increases, confirming its scalability within realistic operational limits.

Table 2. System throughput under load

Load (tx per min)	Sustained TPS	Avg Latency (ms)	Status
10	5	25	Stable
50	12	40	Stable
100	18	70	Degraded
250	20	120	Degraded

5. Discussion

The results of this study demonstrate that blockchain technology can be effectively applied to enforce regulatory compliance and product traceability in nicotine product supply chains. This approach differs from traditional centralized inventory and logging systems. The proposed architecture, as presented in Figure 1, integrates compliance enforcement directly into transaction execution

through smart contracts, ensuring that regulatory rules are applied consistently and cannot be bypassed after the fact. This approach addresses a key limitation identified in prior regulatory and traceability systems, where compliance is often monitored retrospectively rather than enforced in real time.

The functional workflow results confirm that the system reliably integrates product authentication and age verification into a unified process. Product validation occurs before transaction authorization, preventing counterfeit items from entering the retail workflow. Age verification is enforced as a mandatory precondition for transaction execution, ensuring that sales to underage customers are blocked at the system level rather than relying on manual checks or post hoc audits. This tight coupling between traceability, identity verification, and transaction authorization strengthens regulatory credibility and reduces opportunities for circumvention.

From a technical perspective, the successful integration of the mobile application, blockchain network, and off-chain storage demonstrates that hybrid architectures can achieve a balance between decentralization and operational efficiency. The on-chain storage of critical smart contract enforcement decisions and transaction records ensures each transaction is tamper-resistant and auditable, while off-chain databases support responsiveness and scalability. The consistently low and stable transaction latency observed across multiple testing suggests that smart contract-based enforcement does not impose significant delays, hence affirming the practicality of deploying such systems in real-time retail environments.

The throughput and load testing results further indicate that the system scales predictably as transaction volumes increase. Higher loads observe performance degradation, but the behavior remains controlled, preventing system failure or erratic performance. This suggests that the architecture is well-suited for incremental deployment scenarios and can be further optimized through network scaling and infrastructure enhancements. Importantly, the observed performance characteristics are consistent with prior reports on centralized systems that often suffer from single points of failure and limited audit transparency.

Beyond technical performance, the findings have important implications for public health and regulatory governance. By enforcing age restrictions at the point of sale and maintaining immutable transaction records, the system provides regulators with a verifiable mechanism for monitoring compliance and investigating violations.

This changes the focus from waiting to check for problems to actively preventing them, which is especially crucial for stopping underage access to nicotine products and the spread of illegal goods. The transparent audit trail also supports accountability across manufacturers, distributors, and retailers, strengthening trust among stakeholders.

6. Conclusion and Future Work

This study presented a blockchain-based traceability and age verification system for regulated nicotine products, designed to strengthen compliance enforcement and prevent underage access. The proposed architecture embeds product provenance and age restriction logic directly into transaction execution through smart contracts, ensuring that regulatory constraints are enforced consistently rather than monitored retrospectively. By integrating product authentication, identity validation, and transaction authorization within a unified workflow, the system addresses key limitations of conventional centralized enforcement mechanisms.

Experimental results demonstrate that the system achieves low and stable transaction latency while maintaining predictable throughput under increasing load, confirming its feasibility for real-time retail use under controlled conditions. The hybrid architecture strikes a balance between decentralization and performance by recording critical enforcement decisions and audit data on the blockchain, while managing supplementary information through off-chain storage. These characteristics support reliable compliance enforcement without compromising operational efficiency.

Beyond technical performance, the proposed approach contributes to regulatory governance by enabling proactive enforcement and transparent auditability across the supply chain. Preventing underage transactions at the point of sale and maintaining tamper-resistant records strengthens accountability among manufacturers, distributors, and retailers while supporting public health objectives.

Despite the current implementation's strong potential, its scope remains limited to a controlled experimental environment. Deployment in real-world settings will require integration with institutional identity systems, regulatory infrastructure, and production-grade blockchain networks. Nevertheless, the results provide empirical evidence that blockchain-based, contract-enforced traceability systems represent a viable and effective approach for regulating age-restricted products. This study, therefore, contributes both technical and

regulatory insights toward the design of enforcement-capable digital infrastructures for public health protection.

Future work will focus on deployment in production-grade permissioned blockchain environments to evaluate performance under real governance conditions. Additional enhancements will include integration with automated product identification technologies, the adoption of privacy-preserving proof-of-age mechanisms, and extended security evaluations under adversarial conditions. These developments will support scalable deployment and broader adoption of enforcement-capable digital infrastructures for age-restricted products.

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