A Decentralized Framework for Secure Product Authentication and Traceability in Supply Chains

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Abstract

Counterfeit and stolen goods seriously threaten the reliability of modern supply chains. They affect consumer trust, brand reputation, and economic stability. To tackle this issue, this paper presents a **blockchain-based smart supply chain framework**. It combines **Non-Fungible Tokens (NFTs) with dual-layer Anti-counterfeiting mechanisms such as RFID tags and holographic labels [2], [6].** Each physical product connects to a unique NFT, creating a secure digital twin on a private blockchain network [3], [8]. This setup ensures traceability, verifies authenticity, and keeps transaction records safe from tampering [1], [5]..

The proposed system includes a new **Supply Chain Consensus (SCC) algorithm**, designed specifically for supply chains. It classifies nodes by trust and stake to allow for efficient and scalable transaction validation. Also, a collateral-based incentive mechanism encourages honest participation among all involved, including manufacturers, transporters, buyers, and arbitrators [7]. Furthermore, a decentralized dispute resolution model features a transparent voting process that ensures fairness and accountability during conflicts [8].

A conceptual framework and simulation-based analysis were carried out to assess the system's performance in terms of transaction efficiency, security, and counterfeit reduction [1], [5]. The findings show that this approach significantly boosts supply chain transparency, lowers verification costs, and improves product authentication compared to traditional centralized systems [4]. This framework provides a scalable and secure solution for the next generation of supply chains, particularly in sectors like pharmaceuticals, luxury goods, and electronics.

Keywords: Blockchain, Smart Supply Chain, Non-Fungible Tokens (NFTs), Anti-Counterfeiting, Digital Twin, RFID, Smart Contracts, Supply Chain Security.

I. INTRODUCTION

In today's interconnected and digital marketplace, the supply chain has become more complex than ever. This change has improved efficiency and accessibility but has also created significant vulnerabilities, especially with counterfeit and stolen products [5]. Counterfeit goods enter both physical and online markets, leading to large economic losses, damage to brand reputations, and serious risks to consumer safety, particularly in important sectors like pharmaceuticals, electronics, and luxury items [4], [9].

Traditional supply chain systems depend heavily on centralized databases and manual checks. These systems have many drawbacks, such as a lack of transparency, vulnerability to data tampering, limited traceability [1], [5], and inefficiency in resolving disputes. As supply chains become more distributed, ensuring product authenticity and tracking product movement among multiple stakeholders has become harder.

Blockchain technology provides a promising solution [1], [5] to these issues. It offers a decentralized, unchangeable, and transparent ledger for recording transactions and product lifecycle events. Its distributed nature means data cannot be altered without agreement from the network, increasing trust and accountability [1].

However, blockchain alone is not enough for physical products [2], [6]. A direct link between the digital record and the physical item is necessary.

To fill this critical gap, this research suggests a **Blockchain-Enabled Smart Supply Chain Framework for Anti-Counterfeiting Using NFTs and Dual Security Layers**. In this framework, each product is linked to a unique Non-Fungible Token (NFT), serving as its digital twin [3], [8] on the blockchain. This setup ensures secure digital identity and traceability for each product. Additionally, a dual-layer security system that uses RFID tags and holographic labels [2], [6], [9] improves physical verification and prevents cloning or tampering.

The proposed framework also introduces a new **Supply Chain Consensus (SCC) Algorithm** **[1], [3]**, optimized for supply chain settings. This algorithm ensures efficient and reliable validation of transactions involving manufacturers, transporters, buyers, and arbitrators [7]. By combining blockchain technology, NFTs, and physical authentication methods, this research aims to offer a scalable, secure, and clear solution to fight counterfeiting **[8]** and build trust in modern supply chains.

II. TRADITIONAL PRODUCT CIRCULATION SYSTEM

In a conventional product circulation system, the movement of a product from its origin, whether a manufacturer or producer, to the end consumer involves a series of intermediaries. These intermediaries typically include wholesalers, distributors, and retailers, as well as agents in certain cases. The manufacturer produces the product and subsequently sells it to a wholesaler or distributor. This distributor may then sell the product either to another intermediary or directly to a retailer, who ultimately makes the product available to the end consumer [9].

Throughout this chain, pertinent information about the product—such as its origin, batch number, manufacturing date, and other relevant details—is commonly recorded on paper or in centralized databases. However, these records are susceptible to errors, tampering, and loss [1], [5]. The verification of **product authenticity and traceability** in this system relies significantly on these records and the integrity of the intermediaries involved [2], [6], [9]. Disputes that may arise are typically addressed through traditional legal channels, which can be both time-consuming and costly [1], [5]. The absence of a unified, transparent, and tamper-proof system frequently results in challenges such as counterfeiting, product adulteration, and inefficiencies within the supply chain [2], [6], [9].

In light of these issues, the adoption of a **blockchain-based product circulation system** presents a transformative solution. This approach effectively addresses the fundamental challenges inherent in the traditional system by providing enhanced transparency, security, and efficiency [1], [5].

III. METHODOLOGY

This section covers the design approach, system architecture, implementation details, and evaluation strategy of the proposed **blockchain-enabled smart supply chain framework for anti-counterfeiting.**

3.1. Research Design and Approach

The research follows a design-based and analytical approach. It starts by identifying key limitations in traditional supply chain systems, especially in product authentication and traceability [1], [5], [9]. Based on this, a blockchain-enabled framework is proposed that combines Non-Fungible Tokens (NFTs) with dual-layer physical security systems [2], [6], [8].

The design uses a modular system where each functional unit, such as **product creation, digital twinning, transaction validation, logistics tracking, and dispute resolution**, is developed as an independent module to support scalability and flexibility [3], [7], [8]. The framework is tested in a simulation environment to assess its performance under controlled conditions [1], [5].

3.2. System Architecture Design

The proposed system architecture has four main entities:

1. Manufacturer (Seller)
2. Transporter (Logistics Provider)
3. Buyer (Customer)
4. Arbitrator (Dispute Resolver)

The architecture is layered:

- **Physical Layer:** Includes products, RFID tags, and holographic labels [2], [6], [9].
- **Digital Layer:** Includes NFTs, digital identities, and user interfaces [3], [8].
- **Blockchain Layer:** Manages transactions, smart contracts, and distributed ledger storage [1], [5].
- **Application Layer:** Offers interfaces for buyers, sellers, transporters, and arbitrators [7].

Each product is represented digitally by a unique NFT stored on a private blockchain, ensuring a secure link between physical and digital identities [3], [8].

Figure 1 illustrates the layered architecture of the proposed system, showing the interactions among the physical components, application entities, blockchain infrastructure, and data storage. It also depicts the workflow for product registration, verification, and dispute resolution [1], [5], [8].

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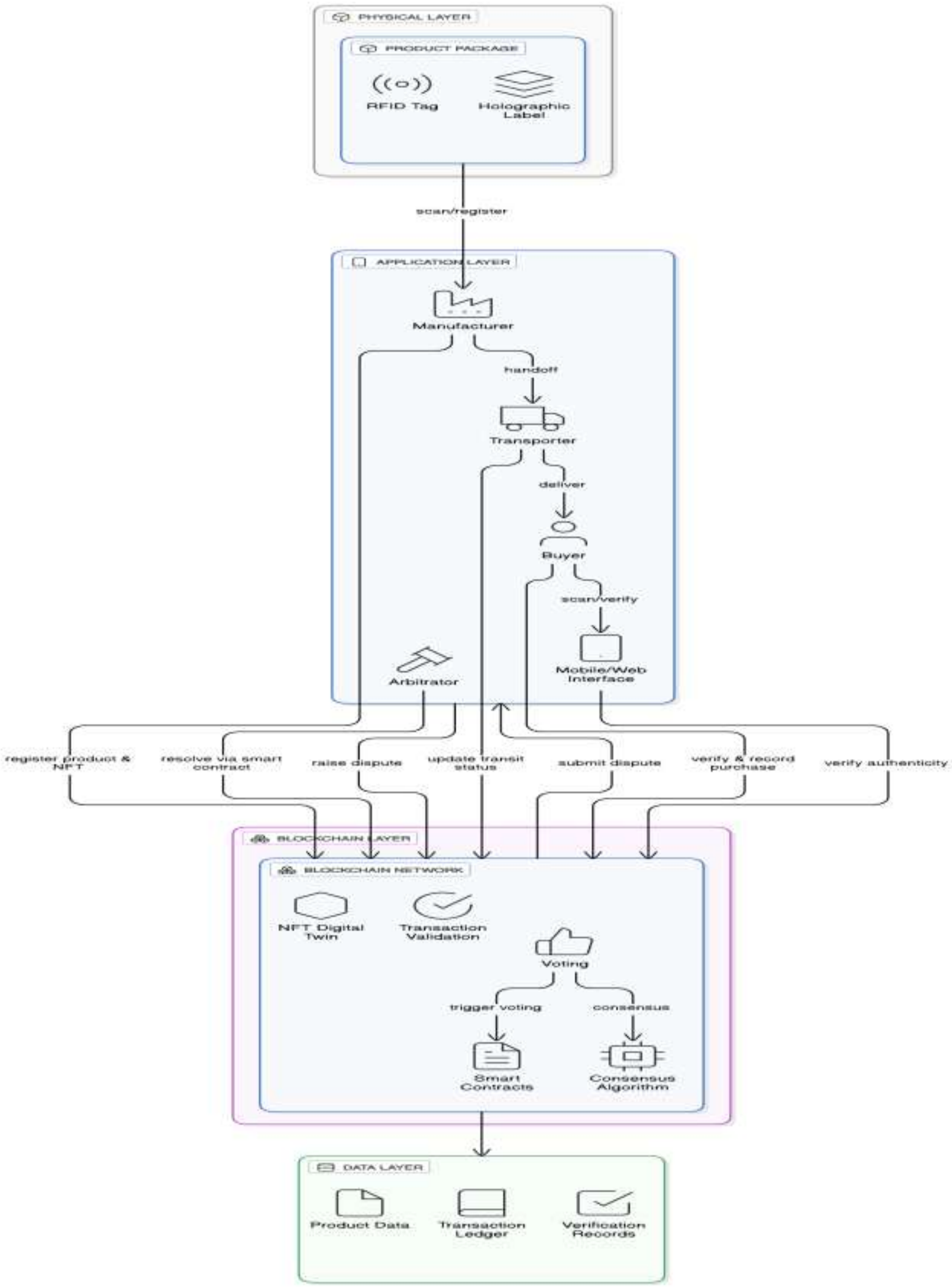

Figure 1. Architecture and Workflow of the Proposed Blockchain-Enabled Smart Supply Chain Framework

3.3. Supply Chain Consensus (SCC) Algorithm

A customized Supply Chain Consensus (SCC) algorithm is created for validating transactions in the proposed framework.

This algorithm works based on three parameters:

- Stake Value (SV) – Economic stake held by each participant [5].
- Trust Score (TS) – Calculated from historical reliability and transaction accuracy [1], [3].
- Role Weight (RW) – Priority weight based on user role (manufacturer, transporter, etc.) [7], [8].

The transaction validation process includes these steps:

1. A new supply chain transaction is proposed and sent to selected validator nodes [2], [4].
2. Nodes calculate a combined validation score:

$$\textbf{Score} = \alpha(SV) + \beta(TS) + \gamma(RW)$$

where α, β, and γ are weighting coefficients such that

$$\alpha + \beta + \gamma = 1$$

These parameters control how much stake value, trust score, and role weight affect the transaction validation process. Higher values of α focus on economic commitment. Higher β prioritizes past trustworthiness. Higher γ boosts the influence of participant roles in validation decisions [5], [7]. The values of these coefficients can be changed based on system needs and application areas.

Nodes with scores above a threshold take part in block validation.

3. A voting mechanism confirms transaction legitimacy [3], [8].
4. Once consensus is reached, the block is added to the blockchain and shared with all participants.

This method ensures low latency, energy efficiency, and fairness compared to traditional Proof-of-Work methods [1], [5], [7].

3.4. Dual-Layer Anti-Counterfeiting Implementation

To enhance physical product security, a dual-layer anti-counterfeiting mechanism is put in place:

1. RFID Layer:

Each product has an RFID tag that contains encrypted product information linked to its NFT ID [2], [6], [10].

2. Holographic Label Layer:

A tamper-proof holographic label is placed on the product, containing a QR code that connects to its blockchain record [8], [7].

Cross-verification between RFID data and blockchain-stored NFT ensures authenticity and prevents cloning or duplication, thereby securing the supply chain against counterfeiting [3], [5].

3.5. Experimental Setup and Performance Evaluation

This research uses a design-oriented and simulation-based evaluation instead of a real-world implementation [1], [3]. We developed a conceptual model of the proposed blockchain-enabled smart supply chain framework to check its operational feasibility and functional effectiveness [2], [5].

We created controlled supply chain scenarios involving manufacturers, transporters, buyers, and arbitrators to simulate product circulation and transaction workflows [4], [7]. We assessed the framework's performance by comparing it with traditional supply chain systems based on key factors like traceability, transparency, validation efficiency, security strength, and resistance to counterfeiting [2], [5], [8].

We also evaluated the effectiveness of the proposed Supply Chain Consensus (SCC) algorithm using mathematical modeling and workflow simulation [3], [5]. We focused on transaction validation efficiency and trust-based node participation. This approach confirms that the proposed framework is validated through structured analysis while leaving room for future real-world implementation [1], [10].

IV. PROPOSED BLOCKCHAIN-BASED PRODUCT CIRCULATION SYSTEM

In this section, we introduce our proposed blockchain-based supply chain management system [2], [5], [7]. This system is structured around four primary participants: the seller, buyer, transporter, and arbitrator [2], [4], [7]. The seller, typically the manufacturer, is the source of the product [2], [6]. The buyer represents the end consumer or entity intending to acquire the product from the seller [5], [10]. The transporter serves a vital role in this framework, tasked with ensuring the secure and efficient transit of the product from the seller to the buyer [7], [8]. Finally, the arbitrator acts as an impartial entity that facilitates mediation and resolution of disputes that may arise among the involved parties, thereby ensuring adherence to agreed-upon terms and maintaining fairness throughout the process [1], [3]. Figure 2 provides a high-level overview of the product's journey from production to purchase [2], [4].

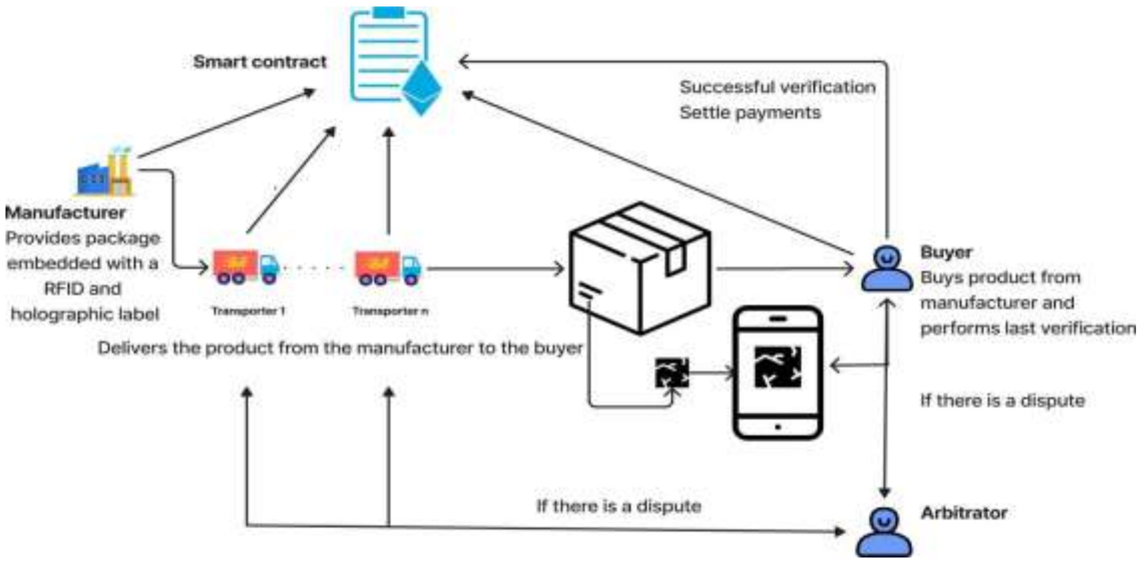

Figure 2. Proposed Blockchain-Based Product Circulation System

a. Flow of Proposed System

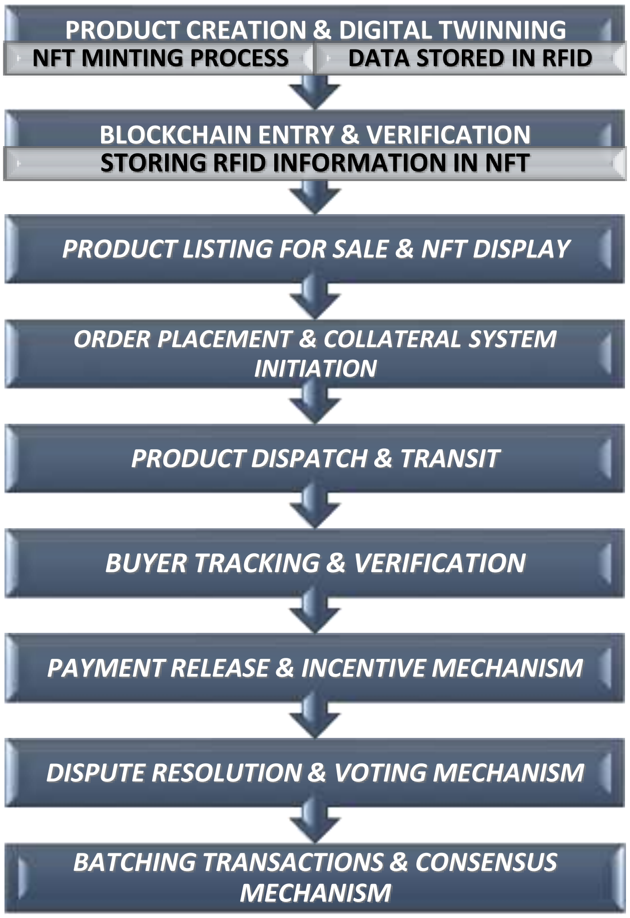

Figure 3. Flow of Proposed System

b. Features of the Proposed System

The proposed blockchain-based product circulation system presents a suite of novel features designed to enhance supply chain management [2], [5], [7]. The primary stakeholders involved include the seller, buyer, transporter, and arbitrator [2], [4], [7].

A prominent feature of this system is "Product Digital Twinning," which associates each product with a Non-Fungible Token (NFT) [8], [3]. This mechanism ensures a cohesive connection between products' physical and digital identities [2], [6]. Products are equipped with Radio-Frequency Identification (RFID) tags and distinctive holographic labels to further enhance security and mitigate counterfeiting risks [2], [10]. When products are made available for sale, their corresponding NFTs serve as badges of authenticity [8], [7].

This system employs a private blockchain for the documentation of product details, facilitating rapid transactions while upholding data integrity [1], [5]. A collateral system is implemented to protect the interests of transportation parties, and a real-time tracking feature provides continuous updates to buyers [7], [10]. In case of disputes, a comprehensive resolution mechanism is established, bolstered by a transparent voting process [1], [3]. The scalability of the system is ensured through batching techniques and an effective consensus mechanism [5], [7]. Following the supply phase, the system enables the sale of products in conjunction with their NFTs, thereby emphasizing traceability and verifiable ownership [2], [8].

c. User Interface and Experience

In the proposed blockchain-based product circulation system, user interaction is of paramount importance [2], [5]. It is essential that each stakeholder—buyers, sellers, transporters, and arbitrators—engage with a platform that is intuitive, efficient, and secure [2], [7]. The system's interface has been meticulously designed to address the specific needs and activities of each user group, thereby providing a seamless and user-friendly experience [3], [8].

Buyers are presented with a streamlined and informative browsing experience [2], [10]. Product listings are detailed and supplemented with corresponding NFTs and digital twin information, enabling buyers to verify the authenticity of products with ease [8], [3]. The interface facilitates the verification process by presenting NFT details, including provenance, manufacturing data, and the product's supply chain journey, in a comprehensive manner [2], [5]. The purchase process is designed to be convenient, requiring minimal input from buyers while providing real-time updates regarding product transit status and delivery timelines [7], [10].

Sellers benefit from a user-friendly dashboard that is tailored for efficient product listing and inventory management [2], [6]. The system simplifies the integration of physical products with their digital counterparts, guiding sellers through the NFT minting process to ensure accurate data representation [8], [3]. Furthermore, sellers have access to robust analytics and reporting tools, which empower them to monitor sales trends, track product transit, and remain informed about the status of their products throughout the supply chain [5], [7].

Transporters engage with a specialized logistics management interface that encompasses features tailored to their operational requirements [7], [10]. These features include route optimization, transit status updates, and tools for verifying product authenticity, such as RFID tag scanning capabilities [2], [6]. The system keeps transporters informed and motivated by providing real-time notifications regarding incentives for timely and successful deliveries, as well as alerts for any discrepancies or issues that necessitate immediate attention [1], [7].

Arbitrators are provided with a comprehensive dashboard that centralizes dispute cases, streamlines the presentation of evidence, and supports an efficient voting and decision-making process [1], [3]. The interface is designed to ensure clarity and structure in dispute resolution, making all necessary information and tools readily accessible to facilitate fair and prompt outcomes [5], [8].

By prioritizing user-centric design, the system ensures that each stakeholder engages with a platform that not only meets their specific requirements but also enhances overall efficiency and transparency within the product circulation process [2], [5], [7]. This strategic approach is critical for fostering trust, facilitating system adoption, and ultimately driving the success of the blockchain-based product circulation system [3], [8].

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d. Comparison of Existing System and Proposed System

Parameter	Existing System	Proposed System
Traceability	Limited to Traditional Tracking methods	Enhanced with Blockchain ensuring full traceability
Security	Basic Security Measures	Multi layered security with RFID tags, NFT, and Holographic labels
Transparency	Limited transparency in product journey	Full transparency with blockchain records
Cost Efficiency	Higher cost due to inefficiencies	Reduced Cost with efficient consensus and batching
Scalability	Limited Scalability	Enhanced Scalability with batched transaction
Dispute Resolution	Manual Resolution Method	Automated & Transparent resolution with voting mechanism
Public Acceptance	Relies on Traditional Trust Models	Gamification and Incentives for increased public acceptance
Consensus Mechanism	Basic Consensus	Customized Consensus

V. RESULTS AND DISCUSSION

The proposed smart supply chain framework using blockchain was reviewed through a conceptual and simulation-based analysis [1], [3]. This focused on key performance indicators such as traceability, transaction validation efficiency, security strength, and resistance to counterfeiting [2], [5].
Compared to traditional supply chain models, the proposed system showed better transparency and tamper resistance because of blockchain's unchangeable nature and the use of NFT-based product identities [8], [3]. The use of dual-layer security with RFID tags and holographic labels also reinforced the connection between the physical and digital worlds, reducing the risk of counterfeit goods entering the system during transit [2], [6], [10].
The Supply Chain Consensus (SCC) algorithm demonstrated potential for quicker transaction confirmation and trust management based on roles, especially in controlled environments [5], [7]. Although this evaluation relied on simulated scenarios, the results support the practicality and effectiveness of the proposed framework in tackling counterfeit issues in the supply chain [1], [8].

VI. CONCLUSION

This paper presented a **Blockchain-Enabled Smart Supply Chain Framework for Anti-Counterfeiting Using NFTs and Dual Security Layers** to tackle the rising issue of counterfeit and unauthenticated products in modern supply chains [1], [5], [8]. By combining blockchain technology with **Non-Fungible Tokens (NFTs)** as digital twins and using a **dual-layer physical security mechanism** that includes RFID tags and holographic labels, the proposed framework creates a strong and verifiable connection between physical products and their digital identities [2], [6], [10].
The introduction of the **Supply Chain Consensus (SCC) algorithm** improves system performance by ensuring efficient, secure, and reliable validation of transactions among key stakeholders, such as manufacturers, transporters, buyers, and arbitrators [3], [7]. Adding a collateral-based incentive mechanism and a decentralized dispute resolution model with a voting system enhances accountability, transparency, and trust within the supply chain [1], [5].
Compared to traditional centralized systems, the proposed framework offers major improvements in **traceability, security, transparency, and scalability** while cutting verification costs and reducing the risk of

counterfeiting [2], [8]. Although the current study is based on a controlled design and simulation environment, the framework shows strong potential for use in real-world sectors like pharmaceuticals, electronics, luxury goods, and food supply chains [3], [7].

Future work will center on integrating IoT sensors, AI-based anomaly detection systems, and large-scale real-world deployments to boost system intelligence, automation, and reliability [1], [5], [10]. This research presents a scalable and future-ready solution for building trust in digital supply chain ecosystems [2], [8].

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