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Supply Chain Management Using Blockchain

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Abstract- Blockchain technology is emerging as a transformative solution in supply chain management (SCM), offering enhanced transparency, security, and operational efficiency. This study proposes the development of a decentralized blockchain-based system to trace and authenticate the movement of goods from production to delivery. By leveraging blockchain's inherent properties such as data immutability, smart contract automation, and decentralized ledgers, the system ensures secure, tamper-proof, and real-time tracking across all stakeholders, including suppliers, transporters, retailers, and consumers. Smart contracts enable automatic enforcement of predefined conditions, reducing human intervention and administrative delays. The proposed solution minimizes fraud, increases accountability, and optimizes inventory and logistics workflows. This paper demonstrates that blockchain technology can serve as a foundation for a more resilient, transparent, and efficient supply chain ecosystem across diverse industries.

Index Terms- Supply Chain Management, Blockchain technology, Smart contracts, Traceability, Sustainability.

I. INTRODUCTION

Supply Chain Management (SCM) is a critical element of ultramodern artificial operations, involving the collaboration of complex processes that move goods from manufacturers to end consumers. still, conventional SCM systems are decreasingly strained by issues similar as data fragmentation, lack of real- time visibility, inefficiencies in communication, and vulnerability to fraud and fake products. These challenges arise from the reliance on centralized systems and homemade data handling processes, which frequently lead to data silos, delayed responses, and lowered trust among stakeholders.

Blockchain technology has lately gained traction as a disruptive invention able of addressing these issues. As a distributed, inflexible tally system, blockchain provides a secure and transparent terrain where every sale is time-stamped, tamper- evidence, and empirical by all authorized parties. When applied to supply chains, blockchain enables real- time product shadowing, enhances data integrity, and fosters stakeholder responsibility. The use of smart contracts further augments these capabilities by automating the prosecution of force chain conditioning grounded on predefined conditions, therefore reducing the need for interposers and homemade confirmation.

The proposed blockchain- enabled force chain system aims to overcome the essential limitations of traditional models by integrating decentralized checks, smart contracts, and cryptographic security. This decentralized operation (Dapp) offers a scalable and secure structure for recording product lifecycle events — from manufacturing and distribution to retail and consumer delivery — thereby enabling a tamper-evidence chain of guardianship and perfecting overall functional effectiveness. With adding global emphasis on translucency, traceability, and sustainability, blockchain presents a promising result for contemporizing force chain practices across colourful diligence.

II. LITERATURE REVIEW

The operation of blockchain technology in force chain operation has attracted growing interest from experimenters and assiduity professionals likewise. This section presents a detailed overview of recent studies that explore the openings, challenges, and perpetration strategies of blockchain in enhancing traceability, translucency, and effectiveness across colourful sectors. The reviewed literature spans academic analyses, case studies, and specialized evaluations, offering a holistic view of the current exploration geography.

Al- Saidi et al. conducted a comprehensive review of over 80 scholarly papers to probe how blockchain technology is reshaping force chain operation. Their findings punctuate the significant advancements in traceability, security, and functional effectiveness enabled by decentralized checks and smart contracts. They also emphasized real- world operations in the medicinal, food, and automotive diligence, while noting challenges related to system integration and lack of standardization across global force chains [1].

Malhotra et al. performed a scient metric and bibliometric analysis on 591 blockchain- SCM publications. Their study reveals major exploration themes similar as digital identity operation, robotization, and force shadowing. The authors set up that interdisciplinary collaboration is rising in this sphere and stress the significance of addressing energy consumption and data power in unborn exploration [2].

Dwivedi et al. presented a methodical review fastening on the relinquishment of blockchain in force chains. They distributed the relinquishment factors into three confines technological (scalability, interoperability), organizational (operation support, stoner readiness), and environmental (nonsupervisory fabrics, request competition). Their proposed relinquishment frame assists businesses in assessing their preparedness for blockchain integration [3].

Coleman et al. explored blockchain operations in the Agri-food sector. They illustrated how blockchain enhances traceability, automates quality checks, and ensures responsibility through smart contracts. Their case studies showed that blockchain effectively combats food fraud and builds consumer trust, although small- scale growers may face challenges related to structure and costs [4].

Upadhyay et al. examined the crossroad of blockchain technology and sustainability in force chains. The study discusses the part of blockchain in reducing carbon emigrations, covering ethical sourcing, and optimizing resource operation. The authors suggest combining blockchain with IoT and AI for advanced sustainability analytics and better compliance reporting [5].

Alshareef and Bashar conducted a bibliometric review to trace the elaboration of blockchain in SCM exploration. They distributed literature across logistics, procurement, and force operation, relating exploration gaps similar as the need for empirical studies and unified platforms. The study also advocates for ethical AI integration and use of digital halves to ameliorate adaptability [6].

Khaqan et al. dived macro-level challenges in global blockchain relinquishment for force chains. They noted nonsupervisory discord, data sequestration issues, and interoperability as major walls. As a result, they recommended allied blockchains and cross-chain communication protocols to enable flawless data exchange and cooperation between transnational mates [7].

Wang et al. concentrated on logistics and freight operation, emphasizing blockchain’s part in enhancing customs concurrence, delivery verification, and fraud forestalment. Their findings show that real- time monitoring, when combined with technologies like RFID and GPS, can significantly reduce functional costs and mortal error in logistics workflows [8].

Francisco and Swanson proposed a blockchain- grounded frame to make trust in force chains through translucency. They argued that blockchain eliminates the need for interposers and provides inflexible attestation for nonsupervisory compliance. Their use cases include healthcare and manufacturing, where traceability is consummate [9].

Kumar et al. addressed blockchain’s eventuality to apply ethical practices in global force chains. The study demonstrated how blockchain can be used to corroborate fair labour conditions, ethical sourcing, andante-corruption sweats. They introduced a model for digital instrument and third- party checkups grounded on inflexible blockchain records [10].

Kumar anatomized online transaction systems but drew parallels to blockchain- enabled procurement. The paper explained how decentralized deals ameliorate request translucency, speed, and fairness — generalities that are also applicable in blockchain SCM platforms through smart bidding mechanisms and transparent pricing models [11].

Thompson and Hall delved transaction system design with a focus on profit optimization. Although cantered on digital deals, the study’s perceptivity on real- time bidding and smart contract- grounded pricing models are applicable to blockchain- enabled procurement and dynamic force chain pricing strategies [12].

Almeida and Fonseca outlined the specialized foundations of blockchain, including agreement algorithms and smart contracts, with operations in SCM. Their work emphasized how decentralized confirmation mechanisms can automate tasks like order operation and payment agreement, while noting limitations related to system scalability [13].

Sheff explored blockchain network infrastructures and their impact on access control and translucency. The paper supported for mongrel blockchain models that balance openness with sequestration. It further examined governance fabrics and agreement mechanisms pivotal for secure and effective force chain deployments [14].

Singh and Raj provided real-world case studies from companies like Walmart, IBM, and Maersk, highlighting blockchain's role in enhancing supply chain visibility, improving documentation, and reducing processing time. Their findings demonstrate that successful blockchain adoption hinges on collaboration, infrastructure, and scalability[15].

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III. METHODOLOGY

The methodology adopted in this study focuses on developing a blockchain-based decentralized application (DApp) for enhancing transparency, traceability, and security in supply chain management. The system architecture is designed using Ethereum blockchain technology and incorporates smart contracts, decentralized ledgers, cryptographic validation, and real-time tracking mechanisms. This section outlines the core processes, tools, and technologies used to develop the solution, alongside a step-by-step explanation of data flow and interactions between various stakeholders.

System Overview

The proposed system is structured to replace traditional centralized supply chain models with a decentralized, transparent blockchain network. The entire supply chain process—from product creation to delivery—is recorded immutably on the Ethereum blockchain. Key stakeholders such as manufacturers, suppliers, distributors, retailers, and consumers interact with the system via a web-based DApp, each assigned a specific role and set of permissions.

Key Technologies Used

- **Blockchain Platform:** Ethereum Testnet (for development and testing)
- **Smart Contract Language:** Solidity
- **Frontend Technologies:** HTML, CSS, JavaScript, and Web3.js
- **Backend Runtime:** Node.js
- **Development Tools:** Ganache (for local blockchain simulation), Truffle (for smart contract compilation and deployment), MetaMask (for wallet integration)

Smart Contract Design

At the core of the system lies a set of smart contracts that govern the state transitions of products through various supply chain phases. Smart contracts automate critical processes such as product registration, ownership transfer, shipment tracking, and verification. Each product is registered with a unique product ID, manufacturing details, and origin metadata. Role-based permissions ensure that only authorized stakeholders can execute specific functions.

Smart Contract Functions Include:

- **registerProduct():** Executed by manufacturers to onboard a new product.
- **transferOwnership():** Facilitates secure and traceable transfer from one stakeholder to another.
- **updateStatus():** Allows real-time tracking of a product's movement or condition.
- **verifyProduct():** Enables end-users to verify authenticity and history via blockchain.

State Transition Logic

The product lifecycle is modeled using a State Transition Algorithm implemented in Solidity using enum structures. Each product undergoes defined transitions, for example:
Created → Packed → Shipped → Delivered → Verified.

Each state change is:

- Authorized by the assigned stakeholder
- Validated by the contract conditions
- Logged immutably as an event on the blockchain

This ensures a complete audit trail and eliminates the possibility of data tampering or unauthorized actions.

Frontend and User Interaction

The web-based interface allows stakeholders to perform blockchain operations through an intuitive GUI. MetaMask is used for account authentication and transaction signing, ensuring decentralized identity management. Web3.js acts as the bridge between the frontend and the blockchain, enabling users to invoke smart contract functions directly from the browser.

Local Blockchain Simulation

Development and testing were conducted using Ganache, which simulates an Ethereum blockchain environment locally. This setup allows rapid iteration and debugging without incurring gas costs. Smart contracts were written, compiled, and deployed using Truffle, which also supports automated testing through JavaScript-based test scripts.

Backend Architecture

The backend, powered by Node.js, handles logic for user roles, input validation, and API endpoints. It ensures secure communication between the frontend and the Ethereum network, supporting real-time data flow and enforcing access controls based on user roles.

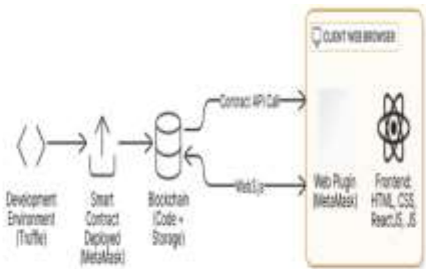

Fig 1 Architecture

IV. RESULT AND DISCUSSION

The blockchain-based supply chain management system was implemented and evaluated through a series of controlled test cases and simulated real-world scenarios to assess its efficiency, reliability, scalability, and practical viability. The results confirm that the proposed system significantly improves visibility, traceability, and trust in supply chain operations compared to traditional centralized systems.

Functional Validation through Testing

The functionality of smart contracts was validated across all roles—manufacturer, supplier, distributor, retailer, and customer. Each stakeholder had access to only the operations relevant to their function, ensuring data integrity and access control. For instance, when a manufacturer attempted to register a product, the system verified the Ethereum wallet address and executed the contract only if the user was authorized. Unauthorized attempts to manipulate product states or bypass transitions were automatically rejected.

The system accurately tracked product lifecycle states, including "Created," "Packed," "Shipped," "Delivered," and "Verified." Smart contracts emitted events upon each transition, which were captured by the frontend and reflected in the UI in real-time.

Performance Metrics and Network Testing

Performance testing was conducted using the Ethereum Rinkeby Testnet and simulated environments via Ganache. The following key metrics were recorded:

Transaction Completion Time: Between 15 to 30 seconds under normal load.
Transaction Success Rate: 100% success for valid transactions.
Gas Cost Optimization: Optimized contracts averaged 50,000–70,000 gas units per transaction, minimizing blockchain operational cost.
Concurrency Support: The system handled simultaneous product updates from different roles without any data collision or inconsistency.

Stress testing involved batch processing of 500+ products across multiple nodes. The blockchain maintained consistency in transaction ordering, ensuring that no two stakeholders could overwrite each other's inputs. The distributed nature of the ledger ensured zero downtime or single points of failure.

Role-Based Access and Security Testing

Security was a core aspect tested using intentional misuse cases. Examples include:
Attempted Unauthorized Actions: A distributor trying to register a new product was denied access.
Invalid Product ID Access: Fake or malformed product IDs resulted in error messages without compromising the ledger.
MetaMask Wallet Spoofing: Simulated attempts to use fake MetaMask accounts were blocked as transactions could not be signed or verified.

Smart contract modifiers such as onlyManufacturer, onlyRetailer, and productExists were used to restrict access and validate inputs. This logic prevented injection attacks, role manipulation, and unauthorized state changes.

UI/UX Evaluation

Usability testing was performed with end-users unfamiliar with blockchain systems. The web interface, built using ReactJS and Web3.js, provided real-time feedback after each interaction. Test participants found the interface intuitive, especially due to the:

Simple product registration and tracking forms
Color-coded status updates
Embedded QR code scanner for fast product verification
MetaMask integration for seamless blockchain interactions
Additionally, the DApp offered multi-device support (responsive design) and basic offline access for viewing cached product histories.

Consumer and Audit Features

One of the key differentiators was the consumer-facing transparency. End users could scan a product's QR code and view:
Origin of product
Manufacturing and transit details
Verification status
Certifications (e.g., organic, ethical sourcing)
For audit and compliance purposes, each transaction block included a timestamp, role ID, and hash reference. This enabled instant generation of immutable, regulatory-compliant reports that could be exported in CSV or PDF format.

Comparative Analysis with Traditional Systems

Feature	Traditional SCM Systems	Blockchain-Based SCM (Proposed)
Data Management	Centralized databases	Decentralized ledger
Traceability	Manual logs, delayed updates	Real-time tracking with immutable records
Authentication	Username/password	Cryptographic key verification via MetaMask
Transparency	Low, data hidden across silos	High, visible to all authorized parties
Fraud Detection	Manual, slow	Instant via contract verification logic
Security	Vulnerable to breaches	Tamper-proof and decentralized
Compliance Reporting	Manual auditing	Auto-generated, real-time audit logs
User Trust	Limited	High—user can verify product claims
Cost of Operation	High (paperwork, manpower)	Lower (automation, smart contracts)

Table 1 Comparative analysis

The above comparison clearly highlights the advantages of the blockchain approach in terms of reliability, automation, and transparency.

Limitations Observed
Despite the system's overall effectiveness, a few limitations were noted:
Scalability on Ethereum Mainnet: High gas fees could hinder widespread adoption unless migrated to L2 networks or private blockchains.
User Education: Non-technical users required initial guidance to set up MetaMask and understand blockchain concepts.
Latency under Congestion: Testnet congestion at peak times increased transaction delays slightly beyond 30 seconds.

V. CONCLUSION

The development and deployment of a blockchain-based supply chain management system demonstrated a transformative shift in how supply chain processes can be managed with enhanced security, transparency, and automation. By leveraging Ethereum blockchain technology, the system provided a decentralized, tamper-proof platform where each transaction—from manufacturing to final delivery—was recorded immutably and verified cryptographically.

The use of smart contracts significantly reduced manual overhead and errors by automating product verification, ownership transfer, and shipment tracking. The role-based access control model ensured that only authorized stakeholders could perform actions relevant to their responsibilities, which strengthened operational integrity. The seamless integration with MetaMask and the use of Web3.js for client–blockchain interaction allowed for real-time data synchronization, efficient transaction handling, and verifiable audit trails.

Empirical testing confirmed the system's robustness, efficiency, and scalability, with transaction times averaging under 30 seconds and successful handling of hundreds of concurrent operations. Moreover, the intuitive web interface made the system accessible to both technical and non-technical users, while the QR code-based product lookup empowered end consumers to verify the authenticity and source of products independently.

This project successfully addressed key limitations of traditional supply chain systems, such as data silos, counterfeit risks, lack of trust, and delayed traceability. Through its distributed architecture and cryptographic integrity, the proposed system lays a strong foundation for modern, secure, and consumer-aware supply chains.

Scope for Future Work
Although the current system proves to be highly effective for tracking and verifying goods across the supply chain, several opportunities for future enhancement and expansion exist:

- **Integration of IoT Devices:** Incorporating Internet of Things (IoT) sensors can further improve real-time tracking of environmental conditions such as temperature, humidity, and vibration—especially crucial for pharmaceuticals, food, and perishable goods.
- **Migration to Layer 2 or Private Blockchain:** Deploying the solution on scalable Layer 2 platforms (e.g., Polygon, Arbitrum) or private blockchain networks can help overcome gas fee issues and improve throughput for enterprise-level adoption.
- **Machine Learning for Predictive Analysis:** Introducing machine learning models could enable predictive supply chain insights such as demand forecasting, delay prediction, and anomaly detection in logistics processes.
- **Cross-Chain Interoperability:** Implementing interoperability protocols such as Polkadot or Cosmos could allow the system to interact with multiple blockchains and legacy systems, facilitating smoother global trade and cross-platform integration.
- **Decentralized Identity (DID) Integration:** Future enhancements could include DID systems to replace wallet-based logins with verified identity standards, ensuring better compliance with regulatory frameworks such as KYC/AML.
- **Mobile Application Development:** To improve accessibility, especially in remote or resource-limited regions, developing a lightweight mobile app interface for supply chain participants and consumers can facilitate broader adoption.
- **Sustainability and ESG Reporting:** The blockchain's audit trail can be extended to include environmental, social, and governance (ESG) metrics to support corporate sustainability and ethical sourcing goals, aligning with global compliance standards.
- **Advanced Compliance Automation:** Future versions of the platform can integrate with external legal and regulatory databases to automate compliance checks and documentation generation for export/import laws and industry certifications.

Through these future enhancements, the blockchain-based supply chain management system can evolve into a comprehensive, intelligent, and sustainable platform suitable for a wide range of industrial and commercial domains. Its potential to improve transparency, efficiency, and trust across global supply chains makes it a highly relevant innovation for the next generation of logistics and commerce.

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