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BLOCKCHAIN TRACEABILITY MODEL IN THE COFFEE INDUSTRY

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Abstract
The global coffee supply chain faces significant challenges in ensuring transparency, traceability, and trust among stakeholders, from farmers to consumers. Traditional systems often suffer from inefficiencies, data fragmentation, and vulnerability to fraud. This paper proposes a blockchain-based approach to enhance traceability and accountability in the coffee supply chain. By leveraging the decentralized, immutable, and transparent nature of blockchain technology, the proposed system records every transaction and transformation of coffee—from cultivation and harvesting to processing, distribution, and retail. Smart contracts automate verification and compliance with quality standards, reducing the need for intermediaries and increasing operational efficiency. The system also empowers consumers with verifiable information about the origin, journey, and sustainability practices associated with their coffee purchases. A prototype implementation demonstrates the feasibility and effectiveness of the approach, highlighting improvements in data integrity, trustworthiness, and end-to-end visibility. This work contributes to advancing sustainable and ethical practices in the coffee industry through technological innovation.

Introduction:

The global coffee industry is a complex, multi-tiered supply chain involving farmers, processors, exporters, importers, roasters, and retailers, each contributing to the journey of coffee from farm to cup. Despite its economic significance, the industry faces persistent challenges in ensuring transparency, traceability, sustainability, and ethical sourcing. Traditional systems often rely on manual processes, centralized databases, and paper records, making them vulnerable to fraud, data tampering, inefficiencies, and limited visibility. These gaps hinder efforts to verify origin, quality, and fair trade practices, affecting smallholder farmers' income and consumers' trust. To address these issues, this project introduces a Blockchain Traceability Model specifically designed for the coffee industry. Blockchain technology, through its decentralized, immutable, and transparent nature, records every transaction securely and permanently, enabling real-time traceability across the entire supply chain. Smart contracts—self-executing agreements coded into the blockchain—automate validation processes, enforce compliance with standards, and execute transactions securely without intermediaries. This enables farmers to log cultivation practices, processors to track handling and packaging, transporters to record shipment conditions, and roasters to input roasting profiles, while retailers provide product data. Consumers, in turn, can scan a code on the coffee product to instantly access its full history, verify certifications, and make informed ethical purchases. The model integrates IoT devices and mobile apps to ensure seamless, real-time data input and monitoring, even in remote farming areas. It also allows role-based access control, protecting sensitive information while maintaining transparency. This approach promotes fairness, improves regulatory compliance, reduces fraud, and encourages sustainable practices. Importantly, it empowers smallholder farmers with digital identities and greater visibility, offering access to better markets and pricing. The model is designed for interoperability, allowing integration with existing certification bodies, supply chain platforms, and government systems via APIs and standardized data formats. Using a hybrid blockchain architecture, the system balances public transparency with private data security, ensuring scalability and efficiency. The intuitive user interface supports multiple languages and requires minimal technical literacy, accompanied by training resources for inclusive adoption. Aligned with the UN Sustainable Development Goals, the model supports responsible consumption and production, inclusive economic growth, innovation, reduced inequalities, and gender equity by recognizing and documenting women's roles in coffee production. With decentralized governance features, stakeholders can propose and vote on improvements, fostering long-term system adaptability and community ownership. Ultimately, the Blockchain Traceability Model offers a transformative solution to reshape the coffee industry into a more transparent, ethical, and efficient ecosystem. It strengthens trust, drives sustainability, and sets a scalable framework that can extend beyond coffee to other agricultural products, paving the way for a digital revolution in global food systems.

I. Related work:

Blockchain technology has gained significant attention in recent years as a solution to traceability challenges in agricultural supply chains, with multiple studies and industry implementations highlighting its potential to enhance transparency, security, and efficiency. Researchers such as Tian (2016) and Kamble et al. (2019) have explored blockchain's role in creating tamper-proof agri-food tracking systems, emphasizing its value in improving food safety and consumer trust. Projects like IBM Food Trust, Starbucks' "Bean to Cup," and Farmer Connect's "Thank My Farmer" have demonstrated real-world applications in the coffee industry, allowing end consumers to trace coffee origins and verify ethical sourcing. Academic efforts by Casino et al. (2019) and Ge et al. (2017) show how blockchain, when integrated with IoT, RFID, and QR codes, can automate compliance checks, support smart contracts, and ensure product quality across every stage of the supply chain. Initiatives like Bext360 and Provenance.io have used blockchain to record payments, verify certifications, and ensure fair compensation to farmers through real-time data, further supporting financial inclusion and transparency. Studies have also proposed hybrid blockchain architectures to address scalability and data privacy, as discussed by Xu et al. (2019), enabling secure, efficient storage by combining off-chain databases with on-chain verification. Mobile-based blockchain solutions like AgUnity have helped smallholder farmers adopt digital recordkeeping in low-infrastructure settings, stressing the importance of user-friendly, multilingual interfaces and offline access. Similar blockchain traceability systems have been piloted in dairy, seafood, and grain sectors, with projects like TraSeable, GrainChain, and Amul showcasing improved

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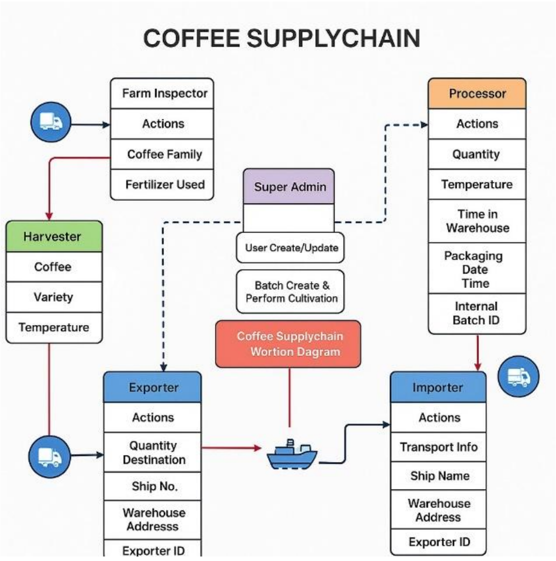
traceability and regulatory compliance. Challenges around adoption, such as infrastructure gaps, resistance from intermediaries, and legal uncertainties, have been noted in studies by Sylvester and Osei-Tutu (2020), pointing to the need for inclusive governance models and adaptable frameworks. Blockchain's potential to digitize fair trade and sustainability certifications has also been recognized, providing a more secure way to verify organic and ethical sourcing claims. Research has further explored the convergence of blockchain with artificial intelligence and satellite data to enhance analytics, yield predictions, and supply chain optimization. Overall, existing work forms a robust foundation for this project, which aims to advance a scalable, inclusive blockchain-based traceability model for the coffee industry, addressing gaps in interoperability, smallholder integration, and end-user accessibility while aligning with global efforts toward ethical, sustainable, and transparent agricultural trade.

II. Proposed method:



(Fig.1.Working process)

1. Data collection and preparations : Data was collected from coffee supply chain stakeholders using mobile forms, IoT sensors, and official records. It was cleaned, standardized, and structured for blockchain integration. Smart contracts validated the final dataset before secure upload.

2. Feature extraction :Key features like farmer ID, harvest date, location, and processing method were extracted from raw data. Each feature was encoded, timestamped, and linked using unique identifiers. The structured data was then prepared for blockchain storage via smart contracts.

3. Preprocessing :Preprocessing involved cleaning, normalizing, and converting raw supply chain data into a consistent digital format. Missing values were handled, and data was structured to align with blockchain schema requirements.

4. Blockchain Integration: The prepared data was systematically added to the blockchain, creating transaction blocks for every event in the coffee supply chain — from harvesting to retail. Each block contained specific data, such as processing updates, shipment records, and retail details, and was linked to the previous block using cryptographic hashes, forming an unbreakable chain of records.

5. Data Storage and Access:All blockchain data was stored in a decentralized ledger to maintain transparency and prevent tampering. Each transaction was encrypted and assigned a unique hash for secure referencing. Authorized stakeholders, such as farmers, processors, and retailers, were granted controlled access to specific data blocks, ensuring data privacy and authenticity throughout the supply chain.

6. Data Analysis and Visualization:The stored data was analyzed to extract valuable insights, such as processing timelines, shipment delays, and quality metrics. Visualization tools like bar charts, flow diagrams, and timelines were used to present data in a clear, accessible format. The module also generated comprehensive reports, enabling stakeholders to monitor transaction histories and verify the authenticity of coffee batches.

7. User Interface Development:A user-friendly interface was developed to provide stakeholders with easy access to blockchain data. Dashboards were designed for each user group — farmers, processors, distributors, retailers, and consumers — allowing them to input data, view transaction histories, and verify product authenticity using QR codes or transaction IDs.

8. Testing and Validation: The system underwent rigorous testing to verify data integrity, blockchain functionality, and user access control. Test scenarios included transaction recording, data retrieval, and QR code scanning to ensure accuracy and reliability. Smart contracts were validated to prevent unauthorized data manipulation and confirm successful integration of all modules.

9. Deployment and Maintenance:

The complete system was deployed on a secure server with ongoing monitoring to identify potential vulnerabilities. Regular updates were scheduled to enhance performance, address user feedback, and align with evolving supply chain processes, ensuring the blockchain model remains reliable and effective.

Userflow diagram

VI . Module and Module description;

Module 1: Importing Necessary Libraries : A high-level architecture for the proposed coffee traceability system together with the stakeholder and their interactions with the smart contract. The stakeholders are envisioned to access the smart contract, decentralized storage system and on-chain resources through software devices that have front-end layer denoted by a DApp (Decentralized Application) which is connected to the smart contract, on-chain resources, and decentralized storage system by an application program interface (API) such as Infura, Web3, and JSON RPC. The stakeholders will interact the smart contract to initiate pre-authorized track transactions in supply chain. Further, they are authorized to access information stored on the IPFS such as the coffee Lot images, and information leaflets.

Module 2: Decentralized Storage System : Decentralized Storage System Provides a low-cost off-chain storage to store supply chain transactions data to ensure reliability, accessibility, and integrity of the stored data. The integrity of data is maintained by generating a unique hash for every uploaded file on its server, and the different hashes for the different uploaded files are then stored on the block chain and accessed through the smart to contract, and any change that any of the occur uploaded file is reflected in the associated hash.

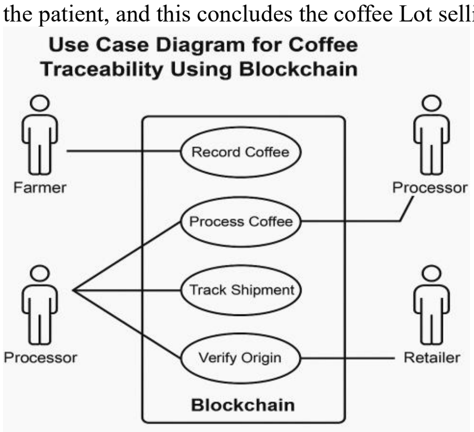
Module 3: Ethereum Smart Contract : Ethereum Smart Contract is used to handle the deployment of the supply chain. The smart contract is central and essential for tracking the history of transactions and manages the hashes from the decentralized storage server which allows the participants to access the supply chain information. Moreover, the functions of the different stakeholders in the supply chain are defined within the smart contract and access to these functions is given to the authorized participants by using modifiers. A modifier is basically a way to decorate a function by adding additional features to it or to apply some restrictions. The smart contract also handles the transactions, such as selling coffee Lots or boxes.

Module 4: On-chain Resources : On-chain Resources are used to store the logs and events that are created by the smart contract allowing track and trace. Moreover, a registration and identity system is used as an on-chain resource to associate the Ethereum address of the different function calls and with the decentralized storage systems to access data files. Finally, their interaction with the on-chain resources will be for obtaining information such as logs, IPFS hashes, and transactions.

Module 5: Manufacturing : Typically, a manufacturer will send a request for approval from the FDA to initiate the manufacturing process of a coffee Lot. Once the FDA approves the request, the manufacturer initiates the manufacturing process and an event is declared to all participants. The manufacturer will upload images of the coffee Lot to the IPFS, and the IPFS will send a hash to the smart contract so that the images can be accessed later by authorized participants. The coffee Lot will be delivered to the distributor for packaging concluding the manufacturing process.

Module 6: Distribution : The next step is the initiation of the distribution process, the distributor will pack the coffee Lot, and an image of the package will be uploaded to the IPFS which will send a hash to the smart contract. Once this step is completed, the coffee Lot packages will be delivered to pharmacies, and this ends the distribution phase

Module 7: Sale/Consumption: The last step in the sequence diagram is related to the interaction between the pharmacy and the patients. Here, the pharmacy will initiate the sale of coffee Lot box and it will be declared to the participants of the supply chain. Then, an image of the sold coffee package will be uploaded to the IPFS, and a hash will be sent by the IPFS to the smart contract. The coffee Lot box will be sold to the patient, and this concludes the coffee Lot selling phase.



1. **Report Generation and Visualization :** The Report Generation and Visualization Module in the Blockchain Traceability Model systematically compiles transaction data across the coffee supply chain, presenting it in a clear and structured manner. After each transaction, the module generates comprehensive reports that include critical information such as crop registration, processing updates, shipment records, and retail sales. It also provides a summary that traces the complete journey of each coffee batch, enabling stakeholders to verify data authenticity and ensure transparency. Visual tools like bar charts, flow diagrams, and timelines effectively convey transaction data, offering a quick and intuitive overview of each stage. Additionally, interactive dashboards allow stakeholders to explore data in detail, facilitating data-driven decision-making and reinforcing traceability throughout the supply chain.

VII. Conclusion :

The Blockchain Traceability Model effectively establishes a secure and transparent system for tracking coffee supply chain data from farmers to consumers. By implementing blockchain technology, it ensures data integrity, prevents tampering, and provides end-to-end visibility of coffee batches. The system enhances stakeholder trust by enabling verified data access and improving operational efficiency through automated transaction recording. Consumers gain valuable insights into product origins, promoting ethical sourcing and informed purchasing decisions. Overall, the model serves as a scalable framework for integrating blockchain traceability in other agricultural supply chains.

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