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Blockchain-Enhanced Traceability Framework for Smart Farming with Integrated Ontology-Based Data Standardization

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***Abstract*— This paper introduces a new conceptual framework to enhance crop traceability within smart farming environments. The framework merges blockchain technology with ontology-based data standardization to address persistent challenges in traditional traceability systems, such as data fragmentation and inconsistencies. The primary goal is establishing a transparent, reliable, and efficient traceability process from farm to table. The methodology employed in this research follows the Design Science Research Methodology (DSRM), involving iterative cycles of designing, building, and evaluating the proposed framework to ensure its effectiveness in real-world applications. The framework offers a promising solution to improve food safety, quality, regulatory compliance, and data-driven agricultural decision-making by capitalizing on blockchain's immutable and decentralized attributes and leveraging standardized data formats facilitated by ontologies. The proposed framework comprises three key components: ontology development, system integration, and blockchain implementation. Ontology development addresses data fragmentation and inconsistencies by providing a common language and structure for data exchange. Meanwhile, system integration ensures seamless data exchange among stakeholders, and blockchain implementation secures and verifies traceability records to maintain data integrity and trust. This integrated system is expected to foster trust and collaboration among all participants in the agricultural supply chain, thereby advancing the efficiency and sustainability of smart farming practices. Through continuous refinement and validation, this research aims to significantly contribute to the practical implementation of advanced traceability solutions in the agricultural sector, ensuring that these systems are robust, scalable, and adaptable to various farming contexts.**

***Keywords*—Agricultural supply chains; blockchain ecosystem; data standards; decentralization; smart contracts.**

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I. Introduction

Recent years have shown a revolution in the agricultural sector, with changes in technologies and farming techniques drastically improving the industry. Smart farming (precision agriculture) combines data from a variety of sources, such as IoT sensors, drones and satellite imagery, Artificial Intelligence (AI), and Machine Learning algorithms [1]. By using these technologies, farmers can maximize or increase productivity by calculating decisions with real-time data, monitoring crop health in real-time, and optimizing resource use [2].

Consumers worldwide demand more transparency and accountability from every step of the food supply chain in a global food market. Good crop traceability is expected to make pinpointing what went awry in a food safety incident easier, stopping foodborne illnesses from spreading and giving consumers confidence in food systems [3]. Traditional crop traceability systems are generally unable to counter data fragmentation and inconsistency, which in turn creates hurdles in monitoring the path of the produce [4]. The conclusive and real answers to these issues are answered best using blockchain technology's decentralization principles.

Blockchain technology was brought in as a platform for cryptocurrencies like Bitcoin but has since been recognized across many areas by features such as decentralization, immutability, and transparency. In agriculture, blockchain has the potential to enhance crop traceability radically, creating incorruptible, legible records of every transaction and movement along the supply chain [5]. When stored in the shared distributed ledger, blockchain allows for the transparent and easy-to-verify traceability of food. However, data standardization is crucial for blockchain to be effectively implemented in crop traceability [6].

Data standardization through the ontology approach provides a well-defined way to specify and categorize data, ensuring interoperability and uniformity among the data from different sources. Therefore, this paper proposed a novel solution that integrates blockchain technology and ontology-based data standardization for crop traceability in smart farming. The framework is expected to help mitigate the current issues by enabling a more transparent, verifiable, and efficient agricultural supply chain ecosystem.

Current crop traceability systems often rely on centralized databases, susceptible to data tampering and inconsistencies [7]. Integrating data from diverse sources poses significant challenges, resulting in fragmented and incomplete information. This lack of cohesive data integration hampers the ability to accurately trace the origin and journey of crops [8], thus undermining food safety and quality control efforts. The complexity of the agricultural supply chain, with crops passing through multiple stages and handlers—from farmers to processors, distributors, and retailers—further complicates the maintenance of consistent and accurate records. The absence of standardized data collection and sharing practices among stakeholders exacerbates this issue, leading to significant gaps in traceability [9].

Moreover, the cost and technological barriers associated with implementing and maintaining advanced traceability systems are substantial. As mentioned by [10], technologies like blockchain, IoT, and RFID, which can enhance traceability greatly, require significant investment in infrastructure, training, and ongoing maintenance. These financial burdens can be particularly challenging for smallholder farmers and businesses in developing regions. Ensuring data security and privacy adds another layer of complexity, as traceability systems must manage sensitive information securely [11]. The initial step to overcome the challenges in crop traceability is to address the data standardization issue, which can be effectively achieved using an ontology approach. This method facilitates harmonizing data formats and terminologies across various stakeholders, ensuring consistency and completeness in traceability records.

Traditional methods of crop traceability in farming rely heavily on paper-based records, manual documentation, and centralized databases [12-13]. While these methods may suffice for small-scale operations, they often lack transparency, are susceptible to errors or tampering, and face challenges in ensuring data integrity throughout the supply chain. Common practices include batch codes, barcodes [14], and serial numbers, which provide limited visibility into crops' journeys and may not meet the evolving demands of consumers and regulators for greater traceability.

Ontology-based data standardization involves creating a structured framework that defines the relationships between different data elements [15]. This approach ensures consistency and interoperability, making integrating and analyzing data from diverse sources easier. By standardizing data, ontologies facilitate seamless communication between different systems and stakeholders, enhancing the overall efficiency and reliability of the traceability process.

This standardized foundation also allows for the seamless integration of blockchain technology, which can further enhance crop traceability by providing an immutable, transparent, and secure ledger for recording each supply chain step.

Recently, blockchain technology has garnered significant attention for its potential to revolutionize various agriculture industries [16]. These characteristics of blockchain, which are its decentralization, incorruptibility, and transparency, make it an excellent tool for improving traceability across supply chains [17]. By writing transaction records to a blockchain, the data can never be changed, providing a permanent record of every part of the supply chain. Blockchain disrupts agricultural practices by introducing greater transparency, efficiency, and traceability to the intricate, interconnected supply chain. Blockchains keep track of each node in a supply chain, facilitating the process of determining crop origins, crop quality, and more [18]. This ensures that every transaction is recorded on an unchangeable ledger so that the farmer, supplier, and final consumer have a guarantee about the truthfulness of the crop and its origin [19]. This facilitates reducing fraud, minimizes food recalls and enhances stakeholder trust.

On the other hand, blockchain streamlines administrative processes and reduces paperwork and transaction costs while improving accuracy and data reliability [20]. In addition to traceability, blockchain works autonomously and supports smart contracts that can automate and enforce agreements throughout the agricultural business circle with the need for intermediaries. These smart contracts help ensure that payments are made and goods are delivered on time, thereby increasing the efficiency of supply chain operations [21]. Blockchain can help these modern farmers tap into new markets and get a better price for their produce by proving how they farm and the quality of crops they grow.

Hence, a conceptual framework integrating data standardization through ontology and blockchain technology is crucial for enhancing crop traceability in smart farming. This integrated approach ensures consistent, accurate, and comprehensive traceability records while leveraging blockchain's immutable and transparent ledger to secure and streamline the supply chain process. Such a framework is essential for improving food safety, quality control, and operational efficiency in modern agricultural practices.

The section briefly introduces smart farming and presents the importance of crop traceability and blockchain technology as viable solutions. Section II depicts how the framework is developed in the context of Design Science Research Methodology. This is followed by Section III, which describes the conceptual framework in detail and discusses implementation strategies, advantages, and challenges of adopting blockchain in the case of crop traceability in smart farming. Finally, Section IV focuses on the conclusion and highlights potential future work.

II. Materials and Method

The study adopted the Design Science Research Methodology (DSRM) approach [22] to construct a conceptual framework for a blockchain-based crop traceability system, augmented with ontology-based data standardization as shown in Fig. 1. DSRM offers a structured framework for guiding the design, development, and evaluation of innovative IT artifacts, ensuring their relevance to practical problems and contribution to both practice and knowledge advancement. The methodology encompasses six key stages.

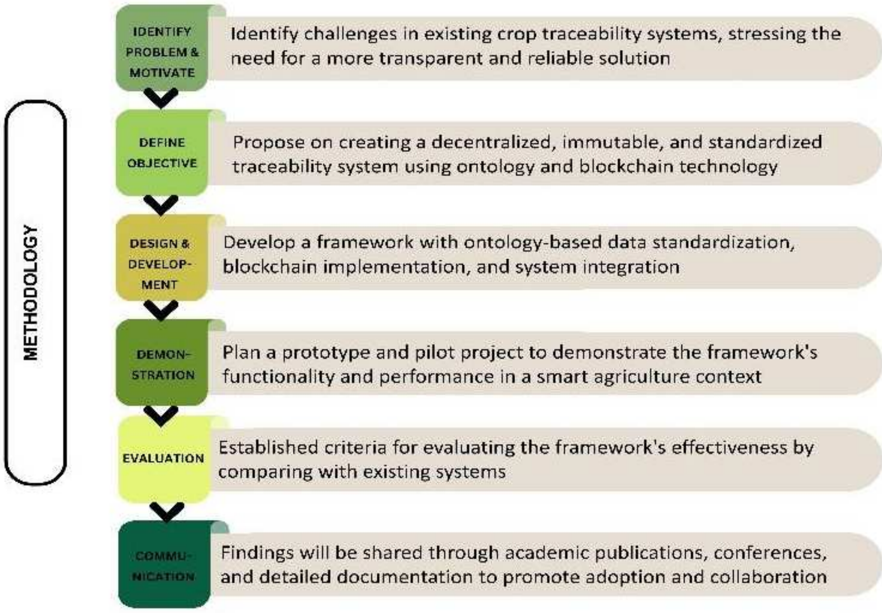

Fig. 1 Study methodology using the DSRM approach

A. Identify the Problem and Motivation

The study identified challenges in existing crop traceability systems, emphasizing the necessity for a solution that enhances transparency and reliability. Traditional systems suffer from data fragmentation, inconsistency, and susceptibility to tampering, undermining food safety and quality. The critical need for a decentralized, immutable, and standardized traceability system is highlighted, with ontology-based data standardization as a critical solution for enhancing interoperability and data integration.

B. Define the Objectives of a Solution

Clear objectives were established to create a decentralized, immutable, and standardized traceability system. Specific goals included developing a comprehensive ontology for crop traceability data, implementing blockchain technology for data recording and verification, integrating the system with existing agricultural technologies, and evaluating its effectiveness in enhancing traceability, transparency, and data integrity.

C. Design and Development

The framework was developed with three main components: ontology-based data standardization, blockchain implementation, and system integration. The ontology is to be constructed through a literature review, expert consultation, ontology development, and validation. Simultaneously, the blockchain system is implemented with platform selection, smart contract development, and integration tools development.

D. Demonstration

A prototype implementation and pilot project in a smart agriculture context is planned to demonstrate the framework's functionality and performance. Case studies with agricultural stakeholders will further showcase the system's practicality and effectiveness.

E. Evaluation

Criteria for evaluating the framework's effectiveness are to be set, including traceability accuracy, data consistency, usability, stakeholder satisfaction, and food safety and quality improvements. Both qualitative and quantitative methods will be employed, comparing results with existing traceability systems to identify areas for further enhancement.

F. Communication

Findings will be disseminated through academic journals, conferences, detailed documentation, and guidelines for stakeholders interested in adopting the proposed system. Knowledge sharing will extend to broader research and agricultural communities to foster innovation and collaboration. Currently, the study is at the third key stage, where the focus is on the design and development of the framework. Details on the proposed framework are depicted in the next section.

III. Result and Discussion

A. Proposed Framework

The conceptual framework provides a comprehensive overview of blockchain-based crop traceability, highlighting its fundamental principles, key components, and integration with IoT devices and smart contracts. It lays the groundwork for the subsequent sections, where the paper will explore implementation strategies, benefits, and challenges of leveraging blockchain for crop traceability in smart farming.

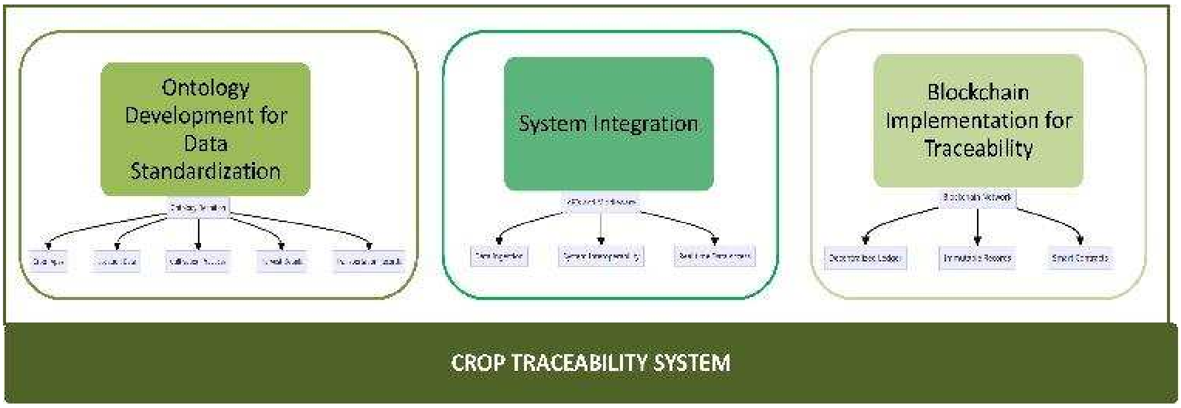

Fig. 2 Conceptual framework integrating ontology-based data standardization, system integration, and blockchain technology for crop traceability

The proposed framework integrates blockchain technology with ontology-based data standardization to create a robust crop traceability system. As shown in Fig. 2, the framework consists of three main components: data standardization, system integration, and blockchain implementation.

Based on the conceptual framework, the first key component, Ontology Development for Data Standardization, involves creating a standardized ontology that defines the structure, semantics, and relationships of crop traceability data elements. The next key component, System Integration, focuses on integrating various data sources, systems, and stakeholders within the agricultural supply chain to enable seamless data exchange and interoperability. Then, the subsequent key component, Blockchain Implementation for Traceability, involves deploying a blockchain-based traceability system that records and verifies traceability events on an immutable ledger, ensuring transparency, integrity, and security. All these key components lead to the development of the Crop Traceability System, an integrated system encompassing the ontology-based data standardization framework, system integration components, and blockchain technology to provide end-to-end traceability of crops throughout the supply chain.

B. Components of Proposed Framework

1) Ontology-Based Data Standardization: The first key component involves developing an ontology that defines the data elements and their relationships relevant to crop traceability. This ontology serves as a common language that standardizes data across various sources, ensuring consistency and interoperability. Key data elements include crop type, location, cultivation practices, harvest details, and transportation records. Once the data is standardized, it can be recorded on a blockchain. Each transaction or event in the crop's journey is logged as a block in the blockchain, creating an immutable record. Smart contracts are used to automate and enforce traceability rules, ensuring that all relevant data is captured and recorded accurately.

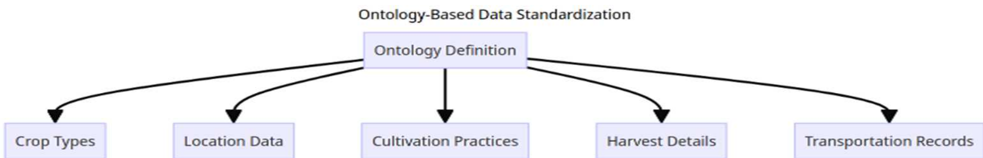

Fig. 3 Component of ontology-based data standardization

As seen in Fig. 3, the Ontology Definition layer involves developing a comprehensive ontology that defines the essential data elements, and their relationships needed for crop traceability. The ontology includes:

- Crop Types: Classification of different crops
- Location Data: Geographic information about where crops are grown
- Cultivation Practices: Details about farming practices
- Harvest Details: Information on the timing and method of harvest

2) Transportation Records: Data on the movement of crops through the supply chain

3) System Integration: The system integration component involves integrating the blockchain-based traceability system with existing agricultural systems and platforms. This integration ensures seamless data flow and accessibility, allowing stakeholders to access real-time traceability information. APIs and other integration tools facilitate communication between the blockchain system and other databases, sensors, and IoT devices used in smart agriculture.

Based on Fig. 4, the Integration layer ensures seamless communication and data flow between the blockchain system and existing agricultural systems. It includes:

- APIs and Middleware: Tools and interfaces that facilitate data ingestion from various sources and enable system interoperability
- Data Ingestion: Mechanisms for collecting and standardizing data from different sensors, databases, and IoT devices
- System Interoperability: Ensuring that the blockchain system can communicate and integrate with other agricultural platforms and databases

- Real-time Data Access: Providing stakeholders with access to real-time traceability information.

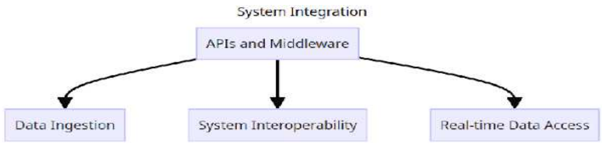

Fig. 4 Component of system integration

4) Blockchain Implementation: Blockchain-based crop traceability involves using blockchain technology to create transparent, immutable, and tamper-proof records of crop-related transactions and movements within the supply chain. At its core, blockchain serves as a decentralized ledger that stores data in a sequential chain of blocks, with each block containing a cryptographic hash of the previous block, timestamped transactions, and other relevant information. By leveraging consensus mechanisms such as proof of work or proof of stake, blockchain ensures the integrity and reliability of data stored on the ledger.

In Fig. 5, the blockchain network layer utilizes blockchain technology to ensure data integrity and transparency. Key elements include:

- Decentralized Ledger: A distributed ledger that records all transactions in the supply chain
- Immutable Records: Ensuring that once data is recorded, it cannot be altered or deleted
- Smart Contracts: Automated contracts that enforce traceability rules and record relevant data entries

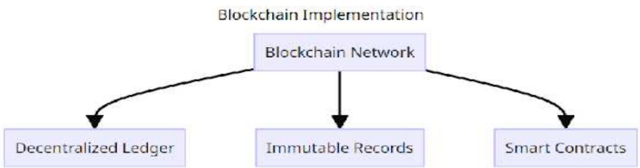

Fig. 5 Component of blockchain implementation

C. Description of Proposed Framework

The proposed framework offers several benefits and positive impacts on the agricultural supply chain, including enhanced transparency and trust due to the immutable nature of blockchain, which makes traceability data transparent and trustworthy, thus boosting confidence among consumers and stakeholders. It also improves food safety and quality by providing a reliable record of each supply chain step, helping identify and address potential issues. The framework supports data-driven decision-making by offering standardized and reliable data, enabling farmers and other stakeholders to optimize practices and improve efficiency. Additionally, it facilitates regulatory compliance, reducing the risk of non-compliance and associated penalties.

However, for an effective blockchain-based crop traceability system, several critical aspects need to be considered, such as:

1) Data Collection: Data collection in a blockchain-based crop traceability system refers to gathering comprehensive information on crop planting, processing, transportation, and distribution according to data sources from IoT, sensors, RFID, GPS, and manual input. IoT devices record the relevant quality parameters, environmental conditions, and logistics details and then securely communicate this information to the blockchain network to store and analyze data in real-time. The fact that blockchain can be combined with IoT helps stakeholders to have non-tampering and accurate status and location of crops every time and everywhere during the whole supply chain, which can increase the overall efficiency, reliability, and transparency of a traceability system.

2) Encoding Data: The collected data must be encoded to a digital format that can be kept on a blockchain. The outcome is that data formats are becoming standardized and interoperable, which enables a much easier and more direct interface and, thus, accessibility to the platforms' levels.

3) Infrastructure (the network of nodes that maintain the blockchain ledger.) This network validates, verifies, and records transactions in an open, decentralized, and secure way, thus maintaining the integrity of the data.

4) Smart Contracts: A smart contract represents a type of asset or property that can be traced and managed via the block or in a node-based supply chain solution; it allows the automation of the traceability agreement execution and enforcement among different stakeholders [23]. Smart contracts enforce pre-set conditions without requiring intermediaries, enabling business logic to be written directly as self-executing code, essential for product authentication, quality control, and compliance verification. They are used for trustless interactions by verifying conditions before triggering transactions between different parties, removing the need to intervene manually, and saving on transaction costs with minimal fraud or errors. Adding their functionality to this solution makes transactions secure and transparent. At the same time, action in the blockchain is permanently recorded, improving overall efficiency, security, and reliability in crop traceability on the blockchain.

5) Data Access and Transparency: Transparency and accountability are achieved as participants in the supply chain (e.g., farmers, producers, distributors, retailers, and consumers) can access data stored on the blockchain. Open access to data guarantees transparency and provides visibility of all processes [24].

Various factors must be considered to introduce blockchain-based traceability systems to the smart farming environment [25]. These are primarily examinations of the technical aspects, e.g., network connectivity, data storage, and computational resources, all needed to satisfy the system's demand. Data privacy and security measures are also necessary to protect the sensitive nature of information recorded on the blockchain (such as personal data, trade secrets, and proprietary information) [26]. Regulatory requirements are necessary that are similar to those that guide data management, consumer protection, and food safety structure [27]. Giving stakeholders up and downstream the supply chain (farmers, producers, distributors, retailers, regulators, and consumers) a voice and a seat at the table is critical to getting buy-in and cooperation. Adoption must be done with technology providers, industry associations, government agencies, and non-government organizations (NGOs) to promote knowledge sharing, capacity building, and dissemination of best practices [3], [28]. In addition, selecting the proper blockchain platform will require scalability, interoperability, consensus mechanisms, governance models, and interoperability and data-exchange capabilities between different systems [29].

IV. Conclusion

Integrating blockchain technology with ontology-based data standardization presents a promising solution to the persistent challenges in crop traceability within smart farming environments. This framework enhances food safety, quality control, and regulatory compliance by creating a transparent and immutable record of each step in the supply chain. The structured approach to data standardization ensures interoperability and consistency across diverse data sources, facilitating seamless integration and real-time access to traceability information. Moreover, stakeholder engagement and collaboration are crucial to successfully adopting and implementing this system. The framework fosters a cooperative environment that promotes innovation and best practices by involving all parties in the agricultural supply chain, from farmers to regulators. Future work will focus on the practical implementation of this framework, evaluating its effectiveness through pilot projects and case studies, and exploring potential enhancements to improve agricultural traceability and sustainability further.

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