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Article

Enhancing Agriculture Products Traceability towards Sustainability

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Abstract: The agricultural industry is undergoing a transformative shift boosted by the Farm to Fork (F2F) strategy, a crucial part of the European Green Deal that directly involves food production. The aim of F2F is to push European agriculture to move from compliance to performance, which will impel farmers to decrease the application of pesticides and fertilizers, improve nutrient management, and reduce emissions, towards a focus shift of greater transparency and traceability in the supply chain. And blockchain technology has emerged as a powerful tool to facilitate this change. The Portuguese Tomato industry plays a significant role in international trade where is ranked in 7th position in the global sales of tomato products in 2022/2023. This paper explores the application of blockchain technology in enhancing traceability within the tomato industry supply chain, as traceability is crucial to improve food safety and meet the requirements of relevant protocols, industrial quality control, and consumer confidence. However, traditional paper-based systems and databases have limitations in ensuring real-time, tamper-proof traceability. Blockchain offers a decentralized, immutable ledger that securely records each step in the tomato production, processing procedures and distribution process. In this paper, we examine the key challenges in tomato traceability and how blockchain addresses these challenges. We discuss the principles of blockchain technology, emphasizing its transparency, security, and decentralization. Moreover, we present case studies and real-world implementations of blockchain in tomato traceability, showcasing the tangible benefits of this technology. Blockchain's role in tomato traceability extends beyond food safety; it empowers the industry and consumers to make informed choices about the products they consume, promotes fair trade, and supports sustainable agriculture. We also discuss the challenges and considerations in adopting blockchain for tomato traceability, including data privacy, interoperability, and scalability. As a conclusion, this paper highlights the potential of blockchain technology to revolutionize tomato industry traceability by ensuring transparency and security throughout the supply chain. It emphasizes the importance of this innovation in ensuring food safety, promoting sustainability, and meeting the increasing demands of conscious consumers. Blockchain's impact on tomato traceability is poised to create a more efficient, trustworthy, and sustainable tomato supply chain for the future.

Keywords: blockchain; traceability; artificial intelligence; disease; pest; prediction; sustainability

1. Introduction

Agriculture, the lifeblood of economies and societies worldwide, plays a pivotal role in sustaining human life and nourishing communities. Yet, behind every harvest and every farm, lies a complex web of transactions, negotiations, and exchanges that shape the agricultural landscape. At the heart of this intricate ecosystem, the concept of responsible production emerges as an indispensable force that carries profound implications for farmers, technicians, consumers, and the sustainability of our global

food systems.

The global food industry is undergoing a profound transformation, marked by an increasing demand for transparency, traceability, and accountability throughout the supply chain. Consumers are more discerning than ever, seeking information about the origins and quality of the products they consume as the carbon footprint related. In this context, the tomato industry faces unique challenges and opportunities, particularly in ensuring the traceability and safety of its products.

Tomatoes are a staple in diets around the world, and the need for effective traceability within the tomato supply chain is paramount. From farm to fork, every step in the production, processing procedures, and distribution process must be documented and accessible to meet regulatory requirements, movements of not finished products ensure food safety, and build consumer trust. Traditional methods of record-keeping, reliant on paper-based systems or centralized databases, have proven insufficient in delivering the level of transparency and security now expected.

This paper delves into a groundbreaking solution to the challenges of tomato traceability: blockchain technology. Originally developed for cryptocurrencies like Bitcoin, blockchain has demonstrated its transformative potential across various industries. It offers a decentralized and tamper-proof ledger capable of recording each transaction or event within the tomato supply chain. Doing so provides transparency, security, and real-time traceability—a trifecta of benefits that can reshape how tomatoes are sourced, processed, and traded.

In the following sections, we explore the principles of blockchain technology, highlighting its transparency, security, and decentralization. We delve into the specific challenges the tomato industry faces regarding traceability, food safety, and sustainability. Furthermore, we will examine case studies and real-world implementations of blockchain in tomato traceability, demonstrating this technology's tangible advantages and transformative potential.

The introduction of blockchain technology in tomato traceability has far-reaching implications. Beyond enhancing food safety, it empowers industry, traders and consumers to make informed choices, promotes responsible options, and supports sustainable agricultural practices. However, this transition is not without its challenges, including data privacy, interoperability, and scalability issues.

As we explore blockchain technology's role in enhancing tomato traceability, we stand at the threshold of a transformative era in the tomato industry. By harnessing the power of blockchain, we can aspire to create a more efficient, transparent, and sustainable tomato supply chain—a vision that aligns with the evolving demands of the global food market and the expectations of an informed and conscientious consumer base.

Increased productivity and efficiency, for example, can be facilitated by using AI [1], which increases economic sustainability. Evidently, AI is utilized to maximize crop harvesting and processing. For example, machine learning algorithms and drones equipped with cameras are employed to ascertain the rate at which vegetables decompose [2]. Furthermore, with assistance from other component technologies, AI makes it easier to sort food supplies while continually checking the degree of sanitation throughout all activities [3].

Transparency is one of the main advantages that AI may provide from the standpoint of social sustainability, especially downstream in a supply chain. For instance, because AI has sophisticated data processing skills that enable tracking the upstream supply chain all the way down to the raw materials stage, it may advise consumers to make more thoughtful decisions about what to buy—choosing things that are created and obtained responsibly [4,5].

2. Literature Review

Based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach, this systematic review statement was developed to assist authors in better reporting systematic reviews and meta-analyses [6]. Although PRISMA can also be used as a foundation for presenting systematic reviews of other forms of research, and notable evaluations of therapies, it has been mostly used to report randomized trials. PRISMA might help evaluate published systematic reviews critically.

The search was done in Scopus and Web of Science Core Collection (WoSCC) databases, in March 2024. To make this search, a query was created with an interception between the columns with a limitation, only journal papers, articles, and reviews from the last 5 years, and written in English.

After applying the query to both WoS and Scopus databases, 63 documents were found. However, by removing duplicates and excluding some articles without the information needed, only 19 papers were used in this research study. These steps are shown in Figure 1. Considering AI and Blockchain is becoming a more used technology, more studies are being made by researchers, making a relevance growth in research work published each year, Figure 2.

In [7] the authors propose consumer-centric practices within food supply chains operating under

traceability systems. The methodological approach adopted for this investigation hinged upon a two-fold study framework, encompassing the sequential validation of a common set of variables. This validation process initially drew on consumer data, and subsequently, supply chain actors' insights were gathered. The context for these studies was set within the sustainable tomato supply chain. The research findings shed light on the fact that consumers place significant importance on values associated with health, trust, quality, nutrition, and safety when considering their acceptance of a traceability system. Also, this work, indicates a pronounced degree of consumer-centricity within the supply chain. Additionally, policymakers may consider the concept of consumer-centricity as a valuable asset in the ongoing enhancement of the food industry.

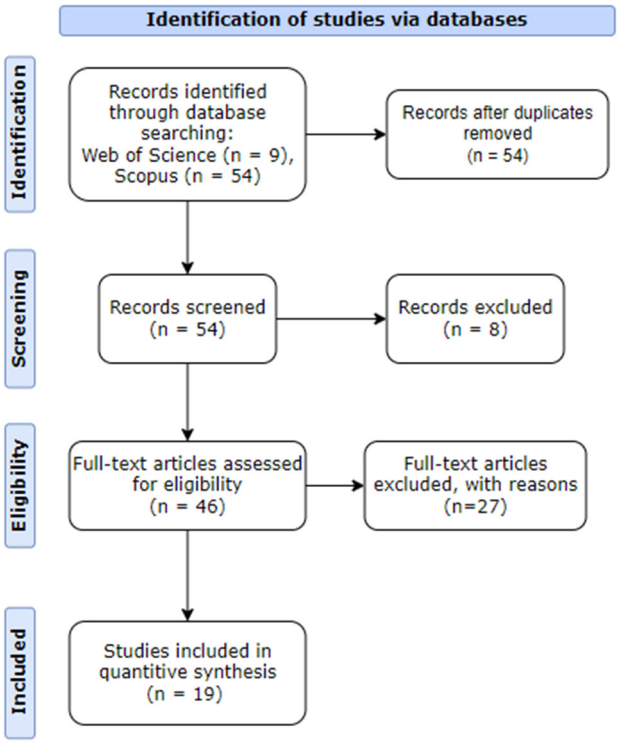

Figure 1. PRISMA Workflow Diagram.

In [8], they talk about the formidable challenges global tomato production industry faces, including the high cost of inputs, the relentless threat of pests and diseases, significant postharvest losses, and the complexities of marketing. Amid these challenges, a new frontier is emerging—the organic tomato production market. The impetus behind this shift comes from heightened consumer awareness, environmental conservation imperatives, and the far-reaching effects of globalization. As a result, farmers worldwide are taking commendable steps toward aligning with organic and other sustainable standards. These standards necessitate the adoption of specific practices, rigorous documentation, third-party verification, and certification. Furthermore, recognizing the need for value addition in the tomato sector has become paramount. It is instrumental in mitigating postharvest losses, driving product diversification, and, in the end, bolstering profitability. This comprehensive review paper endeavors to furnish invaluable insights into the tomato value chain. It is designed to equip stakeholders with the requisite knowledge to ensure the sustainable and thriving production of tomatoes on a global scale.

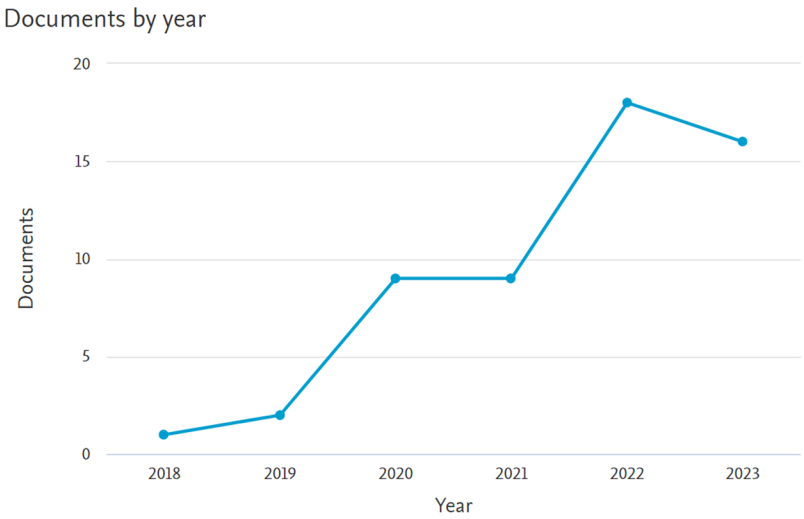

Figure 2. Evolution on eligible studies published by year.

In [9] a comprehensive analysis of material and data-handling processes, thereby laying the foundation for envisioning the practical implementation of AI and BCT. Our initial efforts were directed at mapping the intricate business processes and the interplay at the system level. This mapping exercise allowed us to gain a profound understanding of the material, data, and information flows that stand to benefit from the collaborative application of AI and BCT within the supply chain. The results of this mapping exercise provide compelling visual evidence of the pivotal role that AI and BCT play in the realm of digital supply chain management. The degree of impact on sustainability and data monetization, however, is contingent on the specific parameters and objectives set by the diverse system stakeholders involved in this transformative journey.

The survey in [10], highlights the possibility of developing integrated approaches to research and innovation, to ensure the sustainability of the food system through cooperative actions engaging both private and public actors in the value chain. In [11], a literature review is performed to provide valuable insights into the application of big data analytics and cutting-edge technologies for enhancing the efficiency and effectiveness of the coffee supply chain at every stage. The exploration reveals a spectrum of tools, including wireless sensor networks, cloud computing, Internet of Things (IoT), image processing, convolutional neural networks (CNN), and remote sensing, that hold the potential for revolutionizing the coffee supply chain. In [12], a case study is presented, delving into the implementation of a blockchain-based pork traceability system by Walmart, illustrating the potential of this technology to elevate food traceability standards. The study not only showcases the benefits of blockchain in agri-food, but also acknowledges the hurdles and anticipates future trends in the field. Challenges such as data and cost management, data security, and data integration are explored in depth.

The most popular artificial intelligence (AI) techniques for identifying and categorizing plant diseases include Neural Networks (NN), Logistic Regression (LR), Decision Trees (DT), Support Vector Machines (SVM), K-Nearest Neighbours (KNN), Naïve Bayes (NB), and deep CNN [13].

Classifying the objects in a picture is a popular method of acquiring metrics. This acquisition was carried out by a number of works, including the categorization of insects [14–16] and illnesses in tomato leaves [17,18]. This kind of data can also be acquired by transfer learning strategies. This method was employed by [19,20] in their labour. A pre-trained machine learning model's pertinent components are taken and used in transfer learning.

In [20], the authors used transfer learning to “AlexNet”, “VGG16”, “GoogLeNet”, “MobileNetv2”, and “SqueezeNet” in order to discern between healthy and sick tomato plant leaves, as well as the kind of disease present in the illness instances. The outcomes demonstrated that “VGG16” performed better.

It is possible to gather several kinds of metrics in addition to the basic classification of the items of interest. For instance, Ref. [19] suggested a strategy to categorize tomato ripeness according to colour. When transfer learning was applied, the outcomes surpassed those of other deep learning and machine learning methods applied in previous studies on picture categorization in relation to tomato crops. Pre-processing of the image was done by cropping, scaling, and eliminating the backdrop. Four steps were involved in the background removal process: the first involved transforming the blue channel by setting the green and red channels to zero; the second involved transforming the image into grayscale; the third involved creating a binary mask using Otsu's method [21]; and the fourth involved applying the binary

mask to the colour image.

Nutrient stress in tomato plants is another category of metrics that may be gathered [22,23]. To increase classification accuracy, three pre-trained architectures—“Inception-V3”, “ResNet50”, and “VGG16”—along with two classifiers—Random Forest (RF) and SVM—are integrated with transfer learning in [22]. The outcomes demonstrated that the maximum accuracy was attained by "InceptionV3" alone. The greatest accuracy was achieved by combining "VGG16" with SVM while using the classifiers. A successful machine vision-based experimental sorting technique for tomatoes is shown in [24]. An algorithm was created by the authors to analyse the pictures. Shape, size, ripeness, and flaws were among the characteristics for sorting, and the program gathered these attributes.

The spectral reflectance of damaged leaves on sick plants differs from that of healthy plants due to variations in chlorophyll content. In contrast to healthy plants, sick plants absorb more near-infrared light. Therefore, it is possible to identify damaged plants using reflectance data [25,26]. The late blight infection, which affects various plant species, including tomatoes, was the subject of a study conducted in [25]. It was found that while there are not much visible spectrum differences between healthy and sick plants, there are noticeable differences in the Near Infra-Red (NIR) spectrum.

Artificial intelligence (AI) has revolutionized the food industry, emerging as a powerful tool in ensuring consistent food quality throughout the complex journey from farm to fork. Its applications span various aspects of the food supply chain, offering a holistic approach that not only maintains and improves food safety but also enhances consumer satisfaction.

In blockchain topic, many blockchain-based traceability and information security techniques for agri-food supply chain systems have been presented in the literature. In light of this, the author in [26] has suggested a traceability system based on blockchain, IoT, and Hazard Analysis and Critical Control Points (HACCP). In addition, blockchain has various drawbacks in addition to its benefits. For example, it becomes impractical as data volumes grow. BigChainDB is utilized to bridge this gap and offer a scalable solution in this way. The substantial transparency, efficiency, and support for HACCP requirements of the suggested system are then demonstrated by applying it to an example case.

The suggested plan, however, makes no mention of the items' current ownership information.

Furthermore, a case study about product traceability is provided in [27]. The authors state that tracking a product's origin in a supply chain needs to be clear, impenetrable, and environment adaptive. As a result, they created an origin-chain that combines public and private blockchain. Origin-chain keeps the data both on and off-chain because blockchain storage is limited. Data hashes are stored on-chain, whilst raw files and smart contract addresses are stored off-chain. A case study detailing the real-world use and deployment of origin-chain in industry has also been made available by the writers. They have also spoken about how adaptable the system is, and they have come to the conclusion that the blockchain is a solid choice for Supply Chain Management (SCM) traceability. Nonetheless, the primary issues are privacy and security. Authors in [28] have presented blockchain-based food information security in supply chain management in this context. They claim that a number of methods have been offered to accomplish traceability. These systems, however, are unable to provide the precise traceability needed for the Chinese market. The writers have offered more dependable and effective alternatives based on their investigation and speculative findings. But the actual application of the entire solution is still lagging behind. A case study and a blockchain-based decentralized tracing procedure are presented by the authors in [29]. Auditability and integrity are jeopardized, though. Blockchain and Internet of Things-based solutions are suggested for the Agri-Food supply chain and information security in light of the food safety challenges [30]. They developed a use case for product traceability from the farm to the table and contrasted the outcomes with several implementation platforms, such as Hyperledger and Ethereum. The notions of blockchain and information and communication technology were examined by the writers in [31]. They suggested an assessment tool and an e-agriculture system. The prerequisites for blockchain-based agricultural systems may be obtained using this method. But there are issues with the suggested system's realistic implementation and applicability in a real-world setting. A blockchain-based delivery method that maintains anonymity for tangible goods has been suggested by authors in [32]. They have succeeded in achieving the unlikability, fairness, and anonymity of buyers and sellers. The writers, however, undermined the parties' responsibility. Authors in [33] have addressed the issue of cloning RFID tags after delivery in various way. In order to do this, they employed proof-of-concept and the blockchain of Bitcoin. The authors came to the conclusion that the cost of controlling product ownership is lowered to one USD for almost six transfers following the system's performance review.

Authors have covered the solutions that are now in place and those that have been suggested in [34] in order to preserve reputation and trust when doing online transactions. Next, an agenda for reputation systems has been put up by the writers. The issue of honesty between the vendor and the customer exists on all online transactional platforms. This is because the transaction is not carried out in person

between the two parties.

As a result, a system for maintaining seller reviews in relation to their profile is necessary in order to assist consumers in pre-evaluating both the seller and the items. In [35], a reputation system built on blockchain is suggested. Credibility for data is given in the vehicular networks by the suggested solution. Every communication that is sent between entities is examined based on the traffic in the environment. After that, the network blocks and chains each review. The cars are able to trust the messages they get because of these reviews. Nevertheless, the veracity of the organizations transmitting the signals is compromised. According to the research reviewed above, blockchain technology is being used in supply chain systems centered on agricultural at an exponential rate. It is implemented to improve the current supply chain systems' transparency, traceability, and food safety concerns. Consequently, we have suggested a blockchain-based approach for preserving accountability, auditability, and credibility in agri-food supply chain systems, drawing inspiration from the literature mentioned above.

Artificial intelligence (AI) has become a game-changer in ensuring food quality throughout the complex journey from farm to fork. Its multifaceted applications offer a holistic approach, encompassing various segments of the food supply chain, ultimately leading to enhanced food safety and increased consumer satisfaction.

Here's a deeper look at how AI and Blockchain contributes to a robust food system:

1. Enhanced Visual Inspection and Defect Detection: Computer vision technology combined with AI algorithms can analyze images and videos of food items with unparalleled accuracy. This allows for the detection of various defects like:

- Spoilage (e.g., mold on fruits, discoloration in meat)
- Discoloration (e.g., uneven browning on vegetables)
- Foreign object presence (e.g., plastic fragments in grains)

Studies show AI-powered visual inspection systems can achieve superior performance compared to traditional human inspection methods, with the potential to reduce human error and improve efficiency [36–38].

2. Predictive Quality Analysis: AI systems can analyze vast amounts of data collected throughout the food production process, such as:

- Historical quality data (e.g., past instances of product recalls, customer complaints)
- Environmental conditions (e.g., temperature, humidity, rainfall during cultivation)
- Production parameters (e.g., fertilizer application, storage conditions)
- By leveraging machine learning algorithms and pattern recognition techniques, AI can:
- Forecast the shelf life of products with greater accuracy
- Predict potential quality issues before they occur, allowing for proactive measures.
- Optimize inventory management by identifying products at risk of spoilage and prioritizing their utilization.

This data-driven approach to food quality management can minimize risks and reduce food waste, contributing to a more sustainable food system.

3. Simulating Human Sensory Perception: AI-powered electronic noses and tongues combined with machine learning algorithms can objectively evaluate a product's sensory attributes, including:

- Taste
- Aroma
- Texture
- Appearance

This technology holds significant potential in industries like wine, coffee, and chocolate, where sensory evaluation is crucial but susceptible to human subjectivity and variability.
By standardizing and automating the sensory evaluation process, AI can ensure consistent product quality and reduce dependence on human bias.

4. Optimization of the Food Supply Chain: AI can analyze various data points related to the food supply chain, including:

- Demand patterns
- Transportation logistics
- Storage conditions
- Product quality data
- Utilizing machine learning and optimization algorithms, AI can then:

- Identify and address inefficiencies within the supply chain, such as bottlenecks in transportation or storage issues.
- Minimize product degradation during transportation and storage, ensuring product quality is maintained.
- Optimize delivery routes and schedules to ensure timely delivery of fresh, high-quality products to consumers.

By streamlining logistics and minimizing product loss, AI contributes directly to cost reduction and increased efficiency within the food industry [39].

3. Blockchain Technology and Its Attributes

In this section we identify main stakeholders, their needs, and the requirement for a Blockchain platform to promote data sharing, product traceability and AI to predict diseases and plagues.

3.1. Stakeholders

Various technologies are utilized at every phase of the food journey, and distinct data is recorded on the blockchain for each of these phases, as delineated below:

Provider: Details on the crops, machinery utilized, fertilizers and pesticides applied, etc. The producer/farmer exchanges are documented.

Producer: Details on the farm and the methods used in farming. It is also feasible to provide more information on the weather, animal welfare, or the process of cultivating crops.

Distribution: Information on shipping, routes taken, storage conditions (such as humidity and temperature), transit time for each mode of transportation, etc. Every transaction that takes place between distributors and retailers, who are the ultimate receivers, is recorded on the blockchain.

Retailer: The chain has comprehensive information about every food item, including its amount and quality as of right now, expiration dates, storage requirements, and length of shelf life.

Customer: In the last phase, the customer may scan a QR code attached to a food item with a smartphone that is online or using a web application to view all the information about the product, including details about the manufacturer, supplier, and retail location.

Processing: Details on the factory's apparatus, the techniques employed for processing, batch numbers, etc. Additionally documented are the money exchanges that occur with distributors and manufacturers.

Regulatory and Certification Authorities: - Oversee compliance with food safety and trade regulations. Check conformity with certification in place, if appliable. Access traceability data for audits and investigations.

Blockchain Network Administrators - Maintain and manage the blockchain network, ensuring its security and stability.

The primary objective is to track all the records and phases that tomato passes through until it reaches the end customer, as shown in Figure 3. This is accomplished using a BCT-enabled hash system.

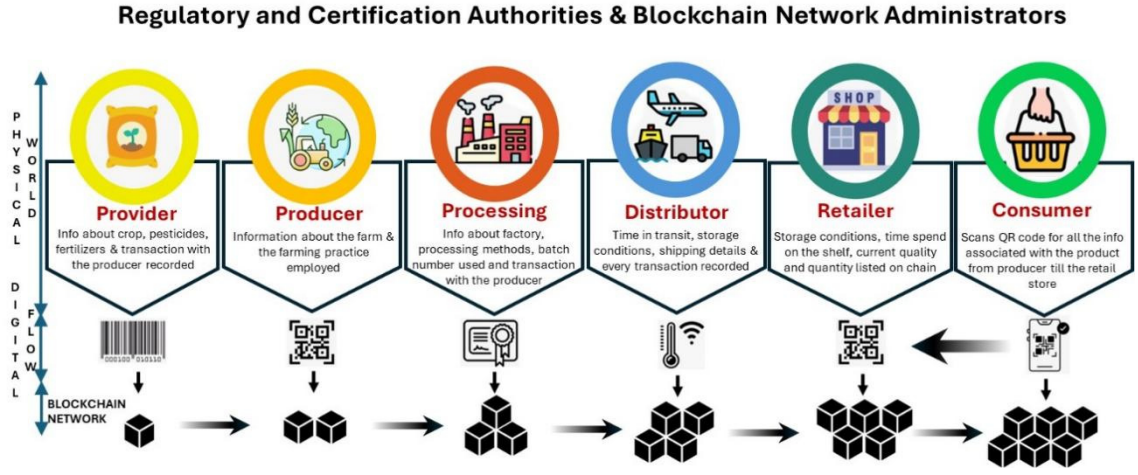

Figure 3. General Agriculture supply chain using blockchain.

3.2. Requirements

The success of a blockchain-based tomato traceability system hinges on a set of critical requirements:

1. Security: Data integrity is paramount. Robust authentication and access control mechanisms must guarantee that information stored on the blockchain is secure and tamper-proof, preventing unauthorized access or manipulation.

2. Scalability: As the system expands to accommodate more participants and data volume, it must maintain efficient performance without compromising scalability.

3. Interoperability: Seamless integration with existing systems and standards within the tomato supply chain is crucial. This ensures smooth information flow and avoids data silos.

4. User-Centric Design: Intuitive and accessible user interfaces cater to stakeholders with diverse technical backgrounds. This empowers everyone involved, from farmers to consumers, to effectively utilize the system.

5. Real-Time Traceability: Stakeholders should have immediate access to comprehensive traceability information, enabling swift and informed decision-making. This includes real-time updates on the location, handling, and condition of tomatoes throughout the supply chain.

6. Data-Driven Insights: Integrated data analytics capabilities provide valuable insights to monitor and improve tomato quality, optimize logistics, and enhance traceability processes.

7. IoT Integration: Seamless interaction with Internet of Things (IoT) sensors is essential for accurate and continuous data collection. This ensures real-time visibility into various aspects of the tomato journey, from farm to table.

8. Regulatory Compliance: Adherence to relevant food safety and traceability regulations is crucial for legal and ethical operation within the food industry.

9. Mobile Accessibility: A mobile application empowers consumers to conveniently access detailed traceability information on the go. This fosters transparency and builds trust with consumers.

10. Data Privacy: Safeguarding personal data and sensitive business information is fundamental. The system must implement robust data privacy measures to comply with regulations and ensure user trust.

By addressing these critical requirements, the blockchain-based tomato traceability system can create a transparent, trustworthy, and efficient ecosystem within the tomato supply chain. This benefits all stakeholders, from farmers and distributors to consumers, by empowering informed decision-making, building trust, and ultimately contributing to a more sustainable and responsible food system.
This platform utilizes various interconnected modules to achieve comprehensive tomato traceability:

1. IoT Sensor Network

Data Acquisition, deployed across farms, these sensors continuously collect crucial data points, including:

- Environmental conditions (temperature, humidity, and soil conditions).
- Input usage (fertilizer and pesticide application details).
- Production Monitoring. This data provides valuable insights into the tomato production and growth process, enabling informed decision-making.

2. Mobile Applications

Farmer Empowerment.Farmers utilize dedicated mobile apps to:

- Input data: Log information about crop cultivation, harvesting, and packaging processes.
- Data Visualization: Gain real-time insights and visualizations of various data points gathered across the supply chain.

3. Data Management

Data Collection and Integration Layer, acts as a central hub for collecting data from various sources, including:

- IoT sensors
- Mobile app inputs
- Third-party data sources (weather, market data)
- Data Lake Storage. All collected data is securely stored in a centralized data lake, facilitating accessibility and analysis.
- Blockchain Integration. Data is securely integrated with the blockchain network for immutability and transparency.

4. Secure Data Storage and Management

Blockchain Network, leverages a distributed ledger technology to ensure:

- Data Tamper-Proofing. Data stored on the blockchain is immutable, guaranteeing its authenticity and preventing unauthorized modifications.
- Transparency and Traceability. Provides a transparent and auditable record of the tomato's journey from farm to fork.

5. Smart Contract Automation.

Automating processes using Smart contracts, self-executing agreements stored on the blockchain, automate various tasks, including:

- Data verification. Ensuring data accuracy and consistency across the system.
- Transaction execution. Facilitating secure and efficient transactions between stakeholders.

6. Data Insights Generation

- Data Processing and Analysis Layer
- Data Analytics Engine for:
  - Quality Control. Improve quality control by identifying potential issues and ensuring consistent tomato quality.
  - Traceability Enhancements. Enhance traceability by providing granular details about each tomato's journey.
  - Advanced Insights. Generate valuable insights for various stakeholders.
  - AI/ML Algorithms. Employ machine learning algorithms to:
    - Anomaly Detection. Detect potential anomalies or quality issues in the tomato production process.
    - Disease Prediction and Early Detection. Predict and identify potential plant diseases at an early stage, enabling proactive measures.

7. User Interface for Accessibility (User Interface Layer)

- Web Portal. Provides a user-friendly web portal for stakeholders like retailers and distributors, allowing them to access:
- Traceability information. Track the journey of each tomato, gaining insights into its origin, handling practices, and other relevant data points.
- Data visualizations. Visualize key data points for comprehensive understanding.
- Mobile App for Consumers. Empowers consumers by enabling them to Scan QR codes printed on tomatoes to access detailed product information, including origin, farming practices, and environmental data. And, Make Informed Choices, gaining transparency into the tomatoes' journey and make informed purchasing decisions based on their values and preferences.

3.3. Information Flow Applied to Tomato Crop

In a blockchain-based tomato traceability system, the seamless flow of information among stakeholders is critical for fostering transparency, trust, and efficiency throughout the supply chain.
Let's delve into data flows between different participants.

1. Farmers

Outgoing Information
Farmers utilize IoT sensors or mobile apps to share data on crop production practices, including:

- Transplanting dates
- Variety of tomatoes grown
- Irrigation system details
- Fertilizer and pesticide application details (including type, quantity, and timing)

Incoming Information
Farmers receive valuable feedback on the quality of their produce:

- Grading and certification information
- Any quality issues detected during transportation or storage

2. Distributors and Packers

Outgoing Information
Distributors and packers contribute information about:

- Packaging details, such as materials and methods used

- Storage conditions (temperature, humidity)
- Transportation data (routes, time in transit)
- This information is added to the blockchain for secure and transparent storage.

Incoming Information

- The source of the tomatoes (farm origin)
- Expected delivery schedules
- Any quality assessments made during the packaging process

3. Retailers

Outgoing Information
Retailers leverage QR codes on the tomatoes to access data regarding:

- Origin and farming practices
- Quality and safety information

Incoming Information
They can provide feedback on the condition of received shipments, reporting any quality issues or discrepancies encountered.

4. Consumers

Outgoing Information
By scanning QR codes, consumers access detailed traceability information:

- Cultivation practices
- Transportation details, including temperature and humidity data

Incoming Information

- Consumers can offer feedback or ratings based on their experience with the product, which can be recorded for future reference.
- They can optionally provide notifications, updates, or requests for specific data, ensuring regulatory compliance.

5. Regulatory Authorities

Outgoing Information
Regulatory authorities have access to traceability data on the blockchain:

- Allowing for audits and verification processes
- Ensuring food safety regulations are met

6. Blockchain Network Administrators

Outgoing Information
Administrators constantly manage the blockchain network, guaranteeing:

- Network stability and security
- Scalability to accommodate a growing user base

This intricate flow of information creates a transparent ecosystem within the tomato supply chain. Each stakeholder plays a vital role in contributing data and leveraging it for informed decision-making, ultimately leading to a more trustworthy and efficient food system for all. The flow of information is facilitated by the blockchain network, which securely stores and shares data among all stakeholders. Smart contracts within the blockchain automate data verification and transactions, ensuring that information is accurate and tamper-proof. This transparent and decentralized system provides stakeholders with real-time access to critical data, promoting trust and accountability at every stage of the tomato supply chain. Overall, the blockchain-based tomato traceability system creates a seamless information flow that benefits all stakeholders, from farmers and distributors to retailers and consumers, by enhancing transparency, food safety, and the efficiency of the supply chain.

4. Tomato Digital Identity

Using blockchain technology for the digital identity of a tomato is an innovative approach with the potential to improve transparency and traceability throughout the food supply chain. The potential benefits also raise some generic and specific challenges:

- Enhanced Transparency. Consumers can access information stored on the blockchain, such as the origin, farming practices, and transportation details of the tomato. This transparency can build trust and empower consumers to make informed choices.

- Improved Traceability. In case of contamination or safety issues, blockchain allows for efficient tracing of the affected product back to its origin. This can facilitate faster recalls and limit potential harm.
- Fraud Prevention. By securely storing tamper-proof data on a distributed ledger, blockchain can help minimize counterfeiting and ensure the authenticity of the product.
- Empowering Farmers. Farmers can benefit from increased transparency by showcasing their sustainable practices and connecting directly with consumers, potentially fetching higher prices for their produce.

Implementation Challenges:

- Cost and Scalability. Implementing and maintaining a blockchain system can be expensive and energy-consuming, especially for small-scale producers.
- Standardization and Adoption. Widespread adoption requires establishing common standards and protocols throughout the industry to ensure interoperability and data sharing across different platforms.
- Consumer Awareness and Trust. Consumers need to be educated about how to access and utilize information stored on the blockchain for it to be truly impactful.
- Data Security. While blockchain offers security advantages, ensuring the integrity and accuracy of the data entered into the system remains crucial.

Blockchain Implementation:

- Unique Digital Identity. Each tomato grown on the farm could be assigned a unique identifier (UID) linked to a specific blockchain entry. This UID could be a combination of alphanumeric characters or a QR code printed directly on a sticker attached to the tomato.
- Data Recording. At various stages of the tomato's lifecycle, relevant data points could be recorded on the blockchain using the UID as a reference. This data could include:
    - Farm Information. Farm location, size, certifications (organic, fair trade, etc.)
    - Planting and Harvesting. Dates of planting and harvesting, seed variety, fertilizer/pesticide details, irrigation methods
    - Transportation and Storage. Temperature and humidity data during transportation and storage, any treatments applied (e.g., ripening agents)
    - Data Access. Consumers would be able to access the information linked to the tomato's UID by scanning the QR code using a dedicated mobile app. This app could be developed by the farm, a third-party organization, or a consortium of stakeholders involved in the food supply chain.

While challenges exist, exploring the potential of blockchain for digital identity in agriculture presents exciting possibilities. Further research, pilot projects like the one described above, and industry collaboration are necessary to address the challenges and pave the way for the wider adoption of this technology in the future. By leveraging the transparency and traceability offered by blockchain, we can create a more informed and sustainable food system for all.

5. Food Integrity

The concept of integrating food integrity and blockchain technology holds immense potential for small farmer cooperatives, particularly in addressing the challenge of disputes and conflicts arising from a lack of transparency. By providing an immutable and secure record of information, blockchain can foster trust and fairer outcomes for all members.

Blockchain technology offers a revolutionary solution for recording and tracking the journey of food products from farm to fork. Unlike traditional methods, blockchain provides a transparent and immutable record of all transactions and activities related to a specific product, creating enhanced trust and accountability within the food supply chain.

Imagine a digital passport accompanying each food item, detailing its entire life cycle. This is precisely what food integrity and blockchain technology offer. By leveraging the power of blockchain, each step of a product's journey, from farm to fork, can be documented in a secure and verifiable manner. This provides crucial benefits for all stakeholders involved:

1. Enhanced Traceability

   Comprehensive Tracking. Every stage of the production and distribution process is recorded on the blockchain. This includes details like:

   - Origin: Farm location, type of cultivation (organic, conventional, etc.)

- Processing: Processing facilities involved, certifications obtained (e.g., fair trade), and any applied treatments.
- Distribution: Transportation routes, storage conditions (temperature, humidity), and any intermediaries involved.
- Retail: Arrival at the final point of sale, expiration date, and batch information.

2. Unwavering Security

Immutable Record. All data stored on the blockchain is immutable, meaning it cannot be altered or deleted once recorded. This ensures the authenticity and integrity of the information, eliminating the risk of data manipulation or fraud.

3. Improved Efficiency

Streamlined Processes. By automating data collection and verification through smart contracts, blockchain technology can simplify and expedite various processes within the food supply chain. This reduces administrative burdens and administrative costs for all involved parties.

4. Building Trust

Transparency for Consumers. Consumers can access this information by scanning a QR code or using a dedicated mobile app. This transparency empowers consumers to make informed choices based on their preferences and values, such as supporting local farmers, ensuring ethical sourcing, or verifying product claims.

5. Fostering Accountability

   Traceability for Businesses. Businesses gain valuable insights into their supply chains, allowing them to identify potential bottlenecks, improve operational efficiency, and ensure regulatory compliance.

6. Empowering Farmers

   Fairer Market Access. By showcasing their sustainable practices and transparent data, farmers can access premium markets that value ethical sourcing and transparency, potentially fetching higher prices for their produce.

In conclusion, food integrity and blockchain technology offer a powerful combination for building a more transparent, secure, and efficient food system. This innovative approach fosters trust among all stakeholders, empowers farmers, and ultimately benefits consumers by providing them with the information they need to make informed choices.

6. A Sustainable and Ethical Force in the Food Industry

The food industry faces significant challenges in balancing sustainability, fair trade practices, and consumer trust. Blockchain technology emerges as a promising solution, offering a decentralized and auditable recordkeeping system that can support numerous initiatives in this domain.

Here's how blockchain fosters sustainability and fair trade:

1. Ensuring Environmental Compliance

   Traceable Supply Chains. Blockchain allows tracking the origin and movement of food products throughout the supply chain. This transparency enables verifying adherence to environmental regulations, such as responsible land management, water use, and waste recycling.

   Carbon Footprint Tracking. By recording energy consumption and transportation details, the blockchain can help calculate a product's carbon footprint. This allows businesses to identify areas for improvement and consumers to choose products with lower environmental impact.

2. Promoting Fair Trade Practices

   Transparent Pricing. Blockchain facilitates transparent pricing structures, ensuring that farmers receive fair compensation for their produce. Every transaction is recorded on the ledger, revealing the distribution of funds throughout the supply chain.

   Empowering Small Farmers. Small-scale farmers often struggle to access fair markets due to a lack of market information and transparency. Blockchain empowers them to showcase their ethical practices and connect directly with consumers, potentially fetching higher prices for their produce.

3. Building Consumer Trust

   Verifiable Claims. Consumers often struggle to verify claims of organic certification, ethical sourcing, or sustainable practices. Blockchain provides a verifiable record of these claims, enabling consumers to make informed choices based on their values and priorities.

Combating Food Fraud. Blockchain allows for tracking product authenticity and origin. This helps combat counterfeiting, mislabeling, and food fraud, ensuring consumers receive the genuine product they paid for.

However, addressing the following challenges is crucial for wider adoption:

- Standardization and regulations: Establishing clear and consistent standards for recording and sharing data on the blockchain is essential for ensuring interoperability and legal clarity across the industry.
- Cost and scalability: Implementing and maintaining blockchain systems can be costly, particularly for smaller players in the food industry. Scalability remains a critical consideration to accommodate the growing demands of the market.
- Consumer awareness: Educating consumers about the benefits of blockchain and empowering them to utilize readily-available tools for accessing information is crucial for building trust and widespread adoption.

In conclusion, blockchain technology presents a compelling opportunity to create a more sustainable and equitable food system. By fostering transparency, accountability, and trust, blockchain empowers all stakeholders, from farmers and businesses to consumers, to contribute towards a more ethical and sustainable future for the food industry.

7. Conclusions

The tomato industry is on the verge of a transformative evolution, driven by the imperative need for enhanced traceability, transparency, and safety within the supply chain. In this paper, we have explored the pivotal role of blockchain technology in reshaping the tomato traceability landscape, addressing the challenges and opportunities faced by the industry. Blockchain technology, originally conceived for cryptocurrencies, has emerged as a revolutionary solution that transcends its roots. Its inherent features—decentralization, immutability, and transparency—have the potential to revolutionize tomato traceability from farm to fork. By providing a secure, tamper-proof ledger that records each transaction, blockchain ensures real-time traceability, promotes data integrity, and enhances consumer confidence. Throughout our discussion, we have illuminated the critical challenges faced by the tomato industry, including food safety concerns, the need for sustainability, and the demand for transparency. Traditional record-keeping systems have fallen short in delivering the level of traceability and security required in today's food supply chains. Real-world case studies and successful implementations of blockchain in tomato traceability have demonstrated its transformative potential. These instances have highlighted the tangible benefits of blockchain, such as improved food safety, consumer empowerment, fair trade, and sustainability support. However, the adoption of blockchain for tomato traceability is not without its complexities. We have explored the challenges, including data privacy considerations, interoperability issues, and scalability concerns. These challenges underscore the need for collaborative efforts from stakeholders across the tomato industry to ensure a seamless transition to blockchain-enabled traceability. In conclusion, the integration of blockchain technology into the tomato supply chain represents a watershed moment in the industry's evolution. It offers an opportunity to meet the rising expectations of consumers, who increasingly demand transparency, safety, and sustainability in the products they consume. By embracing blockchain, the tomato industry can pave the way for a more efficient, trustworthy, and sustainable future—one that aligns with global food safety standards and supports ethical and environmentally conscious practices. As we move forward, it is imperative that stakeholders within the tomato industry continue to explore, experiment, and collaborate to overcome the challenges associated with blockchain adoption. With dedication and innovative spirit, the tomato industry stands poised to leverage blockchain technology as a catalyst for transformative change, ensuring a safer, more transparent, and sustainable tomato supply chain for generations.

Author Contributions

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No conflits to declare.

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No data is available.

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