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Blockchain and Internet of Things Technologies for Food Traceability in Olive Oil Supply Chains

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Abstract: This paper explores the application of Blockchain technology in food traceability, focusing specifically on olive oil. It addresses the significant challenges in the food industry, such as verifying authenticity and detecting harmful substances. The research highlights the potential of Blockchain to enhance traceability by leveraging its decentralized and secure architecture, which ensures data integrity and facilitates rapid monitoring throughout the supply chain. The paper also examines the synergy between Blockchain and the Internet of Things (IoT), which is critical for real-time tracking in product production. The research conducted has led to a practical demonstration through a web application connected to the Ethereum test network, designed for the quality control of olive oil via smart contracts. Overall, this study provides a comprehensive analysis of Blockchain technology and its transformative potential in ensuring food traceability, particularly for high-value commodities like olive oil.

Keywords: blockchain; smart contracts; food traceability; Internet of Things (IoT); supply chain; olive oil

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1. Introduction

The agri-food industry today confronts significant challenges in maintaining food safety and quality, intensified by an increased consumer demand for transparency and traceability from farm to fork. Annually, over 23 million people in Europe suffer from food-related illnesses, leading to more than 5,000 fatalities, underscoring the urgency for robust food safety solutions [1]. Blockchain technology emerges as a promising innovation in this context, offering a distributed, decentralized, and immutable database system that enhances data integrity and security without relying on a central authority [2].

This technology is gaining traction among researchers and industry stakeholders due to its potential to overcome traditional data management drawbacks, such as susceptibility to tampering and limited accessibility. Current agri-food supply chains, often minimally digitized and reliant on paper records or closed electronic systems, are ripe for enhancement. These systems are typically accessible only to specific regulatory bodies, thus limiting the overall transparency and efficiency of the supply chain [3, 4]

The integrity of high-value food products, such as extra virgin olive oil (EVOO), is particularly at risk. EVOO is prized for its nutritional properties and commands a high market price, which unfortunately also makes it a prime target for fraud. Adulteration practices, such as mixing EVOO with cheaper or inferior oils, are rampant, with some estimates suggesting that up to 80% of the Italian EVOO market might be affected [5].

Incidents like the arrest of individuals for exporting counterfeit EVOO in the U.S. [6] and the seizure of large quantities of adulterated oil [7] highlight the scale of this issue. The globalization of food markets further amplifies these risks, making the adoption of technologies like blockchain more crucial than ever in ensuring the authenticity and quality of food products across global supply chains [8].

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Overall, blockchain's introduction into the agri-food sector could significantly revitalize existing systems, ensuring that food safety regulations are met and that the quality of products like EVOO is maintained from production to consumption. The remainder of this paper is structured as follows. **Section 2** explores the potential of blockchain technology in enhancing traceability within the agri-food supply chain, emphasizing how the decentralized and immutable nature of blockchain secures the integrity of product information. **Section 3** examines the synergy between blockchain and the Internet of Things (IoT), discussing how IoT devices provide real-time data crucial for product monitoring and addressing the challenges associated with centralized architectures, such as security vulnerabilities and performance issues. **Section 4** reviews related work, offering an overview of various implementations of blockchain in supply chain management, particularly in the agri-food sector, while highlighting the unique contributions of this paper in relation to existing research. **Section 5** provides a comprehensive description of the olive oil supply chain, identifying key points vulnerable to fraud and outlining how blockchain can improve transparency and security at each stage. **Section 6** presents the technical implementation of the proposed Olive Oil Quality Management System, detailing the design of the smart contract, the server-side processes, and the client interface, all built on the Ethereum blockchain. Finally, **Section 7** concludes the paper by summarizing its contributions and discussing the challenges, limitations, and potential directions for future work.

2. Exploring the Potential of Blockchain Technology in Enhancing Traceability

Blockchain technology has the potential to significantly enhance traceability in the food supply chain [9] by providing a comprehensive record of every stage of the process. It ensures transparency and reliability by securely recording vital information such as product origin, storage and transport conditions, treatments administered, and associated certifications.

With the adoption of blockchain technology, consumers gain full visibility into and assurance of the quality and safety of the food they consume. They are able to track the origin of products, verify compliance with proper storage and transport protocols, and validate adherence to various standards and certifications, including those concerning organic agriculture.

Furthermore, blockchain technology can play a crucial role in identifying and resolving issues within the supply chain, such as epidemics or accidents. It enables rapid identification of the source and destination of products, thereby enhancing the ability to limit the spread of problems and remove unsafe batches of food from circulation.

The use of blockchain for food traceability not only enables consumers to make informed purchasing decisions but also promotes public health guarantees and instills confidence in the food supply. Additionally, traceability is essential in combating counterfeiting and fraud by ensuring that every transaction and activity within the supply chain is thoroughly documented in an anonymous yet seamless manner.

Overall, the application of blockchain technology to food traceability could markedly improve the quality, safety, and trustworthiness of the food supply chain. Consumers would have access to comprehensive information about the journey of their food, while producers, suppliers, and traders could enhance transparency and build trust in their operations. Blockchain technology holds the potential to revolutionize the entire process of food production, distribution, and consumption, thereby providing increased levels of safety, security, and trust for all parties involved [10].

3. Integration of IoT and Blockchain

In the agricultural sector, IoT proves invaluable by aiding in the early detection of plant or animal diseases and facilitating real-time information exchanges between consumers and producers [11]. However, the capabilities provided by IoT are not without concerns. Issues such as security vulnerabilities [12], excessive data traffic, latency, and broadband challenges present significant risks [13]. These are compounded by the reliance on centralized servers for security, protection, and information processing, which can lead to service failures if the central server becomes inefficient [14].

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Further, the reliability of data from IoT devices is crucial; verifying the integrity of data in a centralized architecture is problematic as it can be altered by malicious entities. This underscores the necessity for a decentralized and distributed architecture to enhance data security and reliability. One effective strategy is the use of a distributed service, allowing all network participants to confirm that data remains unmodified and accurate [15].

Blockchain technology, integrated with IoT, serves as a robust framework for data management and transaction distribution. It organizes, executes, and stores data from various IoT devices, enhancing transparency, security, and traceability without third-party involvement [16]. With its decentralized data hosting, blockchain allows data to be shared publicly across multiple servers, ensuring continuous activity and accessibility—an increasing concern with centralized databases.

Moreover, while the blockchain's storage capacity is relatively modest according to modern data storage standards, the transactions it handles are typically lightweight, making it well-suited for IoT device data like temperature, pressure, and humidity, which -though minimal- are crucial for operational integrity. Hardware development platforms such as Arduino, Raspberry Pi, and ESP8266, which utilize technologies like RFID and Wireless Sensor Networks, facilitate the necessary sensing, activation, and communication functions over the Internet [17].

This decentralized approach leads directly to the concept of Smart Contracts, which are self-executing contracts with the terms directly written into code. In the context of agriculture [18], smart contracts can automate and enforce agreements across various stakeholders in the supply chain, ensuring transparency and reducing the need for intermediaries. They can track transactions and quality metrics, manage certifications, and enable secure, automated payments based on data from IoT devices, all while ensuring data integrity and traceability across the blockchain [19].

4. Related Work

Marchesi et al. [20] propose an integrated strategy for blockchain application in agri-food supply chain management. Their methodology emphasizes flexibility, enabling adaptation for different agri-food producers using generic smart contracts configured via JSON files. Biswas et al. [21] introduce a blockchain-based traceability system for wine production using MultiChain, focusing on establishing a secure, private blockchain network. Shahid et al. [22] present a comprehensive solution for agri-food supply chains on the Ethereum blockchain. The system records transactions on the blockchain and interfaces with the Inter-Platform File Storage System (IPFS), providing a secure, reliable storage solution. Their research includes simulations and security evaluations of smart tokens.

Wang et al. [23] leverage the Ethereum blockchain and smart contracts for product traceability, ensuring the authenticity of transaction participants and efficient dispute resolution by recording all events and identifying responsible parties. Malik et al. [24] describe ProductChain, a permissioned blockchain managed by entities in a generic food supply chain including government bodies. It features a three-tier architecture with shards for data reliability, scalability, and controlled access for consumers. Pincheira et al. [25] propose AgriBlockIoT, a blockchain-based system integrating IoT devices for end-to-end supply chain management, validated through a farm-to-plate model using Ethereum and Hyperledger Sawtooth.

Casino et al. [26] propose a blockchain-based model for automated traceability in the food and agriculture sector, featuring a private blockchain and a fully functional smart contract evaluated through a specific use case. Tian [27] propose a real-time food monitoring traceability system combining HACCP, blockchain, and IoT. The system utilizes BigchainDB, merging database and blockchain benefits for transparent and secure traceability. Baralla et al. [28] focus on a blockchain platform for ensuring food provenance in a Smart Tourist Area, integrating IoT devices for cold chain management, monitoring key data like temperature and GPS locations. Marchese and Tomarchio [29] detail a blockchain solution for managing agri-food traceability. Their system, designed for scalability and high availability, is built on a Kubernetes cluster using the Node.js Fabric SDK, tailored for compatibility with existing IT frameworks.

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In comparison to the existing literature, this paper offers several unique contributions and added value to the field of blockchain-based food traceability, specifically within the olive oil supply chain. While many prior studies have explored blockchain applications in agriculture, they often focus on individual components or generalized implementations for traceability. This research distinguishes itself by proposing an end-to-end solution tailored specifically to the olive oil supply chain, which is particularly susceptible to fraud and quality degradation.

A key novel contribution of this paper is the integration of smart contracts within the blockchain framework to automate and verify quality metrics at critical stages of production. By utilizing real-time data from IoT devices, the system ensures that essential quality indicators such as acidity and pesticide residues are securely recorded and permanently linked to each batch of olive oil. This level of automation not only enhances transparency but also significantly reduces the risk of tampering or human error.

Furthermore, the paper introduces a scalable architecture that seamlessly integrates traditional supply chain management systems with decentralized blockchain technology. This architecture is designed to be adaptable for other high-value agricultural products, offering a potential blueprint for broader adoption in the agri-food industry.

Finally, this study offers a practical demonstration of the proposed system by developing a web-based application connected to the Ethereum test network. This application provides a user-friendly interface for stakeholders in the supply chain to interact with the blockchain, ensuring real-time tracking, certification, and verification of olive oil quality. The practical implementation presented in this paper bridges the gap between theoretical research and real-world application, providing a foundation for future advancements in blockchain-based food traceability systems.

5. Description of Olive Oil Supply Chain and Identification of Points Vulnerable to Fraud

The olive oil production and marketing chain involves various actors, as described in the following:

5.1. Producer of Fertilizers and Insecticides:

This actor plays a crucial role in this chain. Their responsibility is the production of fertilizers and insecticides, which will be available in agricultural shops. Packaged, the fertilizers provide detailed specifications for their safe and effective use.

These specifications, which typically include information such as application time, application method, ratio of active substances to water and storage method, can be incorporated into smart contracts. These contracts are created to validate or invalidate the efficiency and quality of each product during the production process.

In this process, when the production is ready, the producer can compose all the smart contracts associated with each product. These contracts are initially blocked. With each sale of a product, that product moves into the pending phase, i.e. it is subject to evaluation and validation, paving the way for the continuation of the agricultural supply chain.

5.2. The Agronomy Shop/Store:

The role of the store is focused on providing producers with full information on the usage specifications of the fertilizers and insecticides they intend to purchase. In addition, it has the obligation to ensure that the fertilizers are stored correctly, in compliance with all relevant standards.

At this point, some of the smart contracts associated with the storage of products may switch from blocked to unblocked status. For example, if storage is carried out as appropriate, a lot-based smart device can automatically validate the conditions of the storage-related smart contract. Thus, the corresponding smart contract will be moved to the unblocked status, signaling the completion of the necessary conditions for the continuation of the agricultural supply chain.

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5.3. The Agronomist or the Agricultural Consultant:

The agronomist plays a critical role in the described production chain. His/her task is to analyze farming conditions, i.e. to conduct plant and soil analyses, and to recommend the appropriate amount and type of fertilizer required by the crop of the farmer (producer) he/she is advising. At this stage, the process of purchasing the necessary formulations has been completed, including information such as the quantity of formulations, the amount of elemental macronutrients or micronutrients depending on the fertilizer, the type of formulation and the price.

The transaction in question moves to the blockchain, enabling transparency and security. Through the blockchain, this transaction is accurately captured, ensuring the integrity and unambiguous recording of its details. The blockchain facilitates the efficient and secure management of transactions at this critical stage of the agricultural supply chain.

5.4. Farmer/Producer:

As the owner of the olive grove, the farmer takes responsibility for a multitude of agricultural processes that contribute to the production of olive oil. The farmer applies fertilizers and insecticides based on the instructions given by the agronomist and the agronomy shop, harvests the olives, and then transports the fruit to the mill. Throughout the year, the farmer fertilizes, sprays the insecticide, and carries out other necessary operations. For reasons of simplification, operations not directly related to the safety of the olive oil or for increasing its market value are not recorded.

At this point, smart contracts previously created by the manufacturer are validated in order to make verifications. For this purpose, it is convenient to connect loT devices to the fertilizer and insecticide spraying mechanisms, called chemical sensors. Chemical sensors detect and convert chemical information into electrical signals, providing qualitative or quantitative information on specific chemical components. Chemical sensors are also placed in the soil, allowing comparative analysis of the values of elements before and after fertilization.

By placing chemical sensors in the soil and performing a comparative analysis of the data, disproportionately high levels of sodium may be detected after fertilization. This may signal illegal or improper fertilizer use by the producer, and therefore the state can intervene and investigate the case based on valid monitoring information. In addition, at this point, all information regarding the date of harvesting of the fruit, place of production and other information that increases the market value of the product is recorded. This information is provided by the Global Location Number (GLN) that identifies the physical location, legal entity, and GPS coordinates of the farmer's estates, allowing confirmation of product origin. Specifically, if the information shows that the area is registered as a PDO (Protected Designation of Origin), this confirms the corresponding contract created by the state PDO product certification body.

5.5. The Processor/Elaborator:

The processor has the role of converting the fruit into olive oil, taking great responsibility for the final quality of the product. To control the temperature, a special intelligent temperature measuring device can be used. If the temperature exceeds 27 degrees Celsius, the relevant smart contract is not validated, and this information becomes visible to the other members of the chain. These members reach decisions on the further management of the batch in question. In such cases, the product is usually not destroyed, but its value is reduced, as excessive temperature is not considered compatible with the "cold export" label. Usually, water recycled in the softener shell is used to reduce the temperature. However, this practice can also have a negative impact on the quality of the olive oil. Consequently, each mill must carefully monitor the temperature to maintain its reliability in the production chain.

The olive oil is weighed and transferred to the storage tanks. The result of each weighing process is stored in a special block on the blockchain. If the mill has imported oil from more than one producers, each producer's weighing is recorded separately and then incorporated into the overall result.

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5.6. State Certified Chemical Testing Laboratory:

Once the final olive oil product is produced, a trader or dealer approaches either the mill or the producer to purchase the product. To set the price, and also to put the right label on the packaging, specific analyses are carried out on the olive oil product.

The first analysis is a simple chemical analysis that gives values for acidity and K. Next, an analysis for pesticide residues is carried out. This is followed by the analysis of defects, but only if no defects are found and the chemical analysis shows values of acidity below 0,8, K268 below 0,22 and K232 below 2,5. The oil is then considered to be extra virgin olive oil. If any of these three chemical analysis indications exceed the stated limits or the median of the defects is between 0 and 2,5, then the oil is downgraded to virgin.

These processes and their results are entered into the blockchain, some manually (sensory analysis and defect analysis are done by teams of expert tasters) and others automatically, such as chemical and pesticide residue analysis. Depending on the results, the corresponding smart contracts are validated or cancelled.

After the completion of all the above procedures, once all the contracts have been validated, the contract for the sale of the olive oil is also validated.

5.7. Olive Oil Standardization:

At this point, all contracts relating to the quality of olive oil have been ratified or cancelled. Depending on these contracts, the corresponding label will be affixed. The more contracts that have been validated, the higher the price of the olive oil on the shelves. If the oil is deemed unfit for consumption, it will be placed in the category of industrial oils. Before standardization, an additional check should be carried out to avoid any impurities. This check is carried out by the state-certified chemical laboratory, and automatically, once completed, it is passed to the blockchain. If this contract is not validated, the trader might face legal issues because the product does not meet the category/label that he/she wishes to apply to sell in the market.

5.8. Storage/Transfer:

The conditions that transport and storage companies need to be aware of are light exposure, humidity, and temperature. All these conditions can be automatically controlled with smart devices. The data they collect are also passed to a new block on the blockchain and in turn validate three more smart contracts. Another control that could be added is the regular monitoring on the condition of the product with vibration detection, data that will be shared between the transport company and the merchant.

5.9. Retail Shop:

The conditions to be checked are the same as those monitored during transport and storage.

5.10. Consumer:

Finally, the consumer who chooses the product will be able to scan the barcode and see all the smart contracts' data relating to the product, such as: origin, acidity, K values, polyphenol and vitamin E content, harvest date and any other information that can ensure confidence of the consumer towards the product, as well as provide added value to the oil. Data such as the selling price from the producer to the trader and other sensitive data of the companies involved are not visible to the consumer.

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6. Blockchain Application for Traceability of Olive Oil Quality at Critical Supply Chain Points

6.1. Overview of Data Required for Olive Oil Traceability

According to the description of the supply chain provided in the previous section, the data to be collected to achieve traceability in olive oil supply chains are of three main types: lot data, chemical analysis data, and organoleptic data. These are summarized in Table 1.

Table 1. Origin of data and types of data for quality and traceability assessment.

Lot data	Chemical analysis data	Organoleptic data
Location	Halogenated solvent data	Value for the fruity
Date of harvest of the fruit	Heavy metal detection data	Value for the bitter
Weight of olive oil	Detection data of plasticizers	Value for the spicy
Melting temperatures	P.A.H. detection data - benzo a-pyrene	Median value of defects
Chemical sensor data in the field before fertilization	Pesticide residue detection data	
Chemical sensor data in the field after fertilization	Detection data of "dehydrated" sterols	
Chemical sensor data during spraying	Garden quantity data	
Dates of spraying	Fractional data of theoretical and experimental value of ECN42	
Moisture level data during transport/storage and while on the shelf	Fatty acid composition data	
Light exposure data during transport/storage and while on the shelf	Sterol analysis data	
	Data Alkyl ester percentage	
	Data pyrophosphate percentage	
	Data on the content of 1,2 and 1,3 diglycerides	
	Data on a-tocopherol content	
	Data on total phenol content	
	Moisture content and volatile matter data	
	Data Percentage of foreign materials	
	Peroxide number data	
	UV absorption coefficient data	
	Acidity value data	

All the necessary smart contracts within this supply chain can be implemented by a state actor. Before creating the corresponding smart contracts, the state actor may receive recommendations by the following blockchain entities: fertilizer/pesticide/insecticide producer, organic agri-food certification body, state certified chemical laboratory, National Transparency Authority.

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6.2. Technical Overview of an Olive Oil Quality Management System Using Blockchain

In the following, we focus our attention on the part of the olive oil supply chain that features a high degree of automation, namely the part of the analysis of the final product before standardization, and we present a blockchain application tailored to the needs of that specific part. The choice was made knowing that analysis laboratories have a high degree of automation, and they already store analysis results in databases. The aim was to highlight blockchain technology on a small scale, with high scalability to any product tested in the laboratory and, above all, easy access to unmodifiable data. It is worth highlighting that, within a blockchain, the data are uploaded in real time and are controlled by means of smart contracts also in real time, which is important when it comes to countering fraud.

In the development of our application, two main actors were identified: a state-certified laboratory, on one hand, and end-users on other, which may include consumers, the state and traders who buy olive oil. The latter acquire olive oil from the producers with a view to securing an agreement that is fully transparent and ensures fair pricing for each party.

Eleven quality parameters have been defined as part of the quality assurance of olive oil, namely:

1) Acidity
2) K268
3) K232
4) Median of defects
5) Polyphenol content
6) alpha-tocopherols (vitamin E)
7) Pesticide residues
8) Insecticide residues
9) Plasticizers
10) Dehydrated sterols (adulteration index)
11) Celsius temperature at the time of oil extraction

The developed blockchain application is part of an Olive Oil Quality Management System designed to ensure the traceability of quality-related attributes. By leveraging blockchain technology, the Olive Oil Quality Management System creates an immutable and transparent record of quality metrics for olive oil batches. The system employs a smart contract deployed on the Ethereum blockchain, managed via a Node.js and Express framework. The design depicted in XXX encompasses key features, including the system architecture, the server-side implementation, and the client-side interface, providing an overview view of the application's structure and functionality. Through the use of smart contracts and a robust server-client architecture, the system enhances traceability and ensures the confidentiality and reliability of quality assessments, addressing critical challenges in the olive oil industry.

As illustrated in Figure 1, at the core of the application is the Ethereum blockchain, interfacing through Infura and managed using a MetaMask wallet for secure transaction signing. The blockchain component hosts the smart contract responsible for storing and managing quality data. A Node.js and Express server acts as an intermediary, facilitating communication between the blockchain and the client interface. The server processes CSV files containing quality metrics, invoking smart contract functions to record this data permanently on the blockchain. Additionally, the server provides API endpoints for retrieving and validating quality data, which are tested using Postman. The client interface, built with HTML, CSS, and JavaScript, allows users to input batch numbers and retrieve corresponding quality information. It also performs real-time quality checks by asynchronously calling the server's API. This architecture highlights the seamless integration of blockchain technology with conventional web development frameworks, ensuring a robust, secure, and user-friendly system for quality management in the olive oil industry.

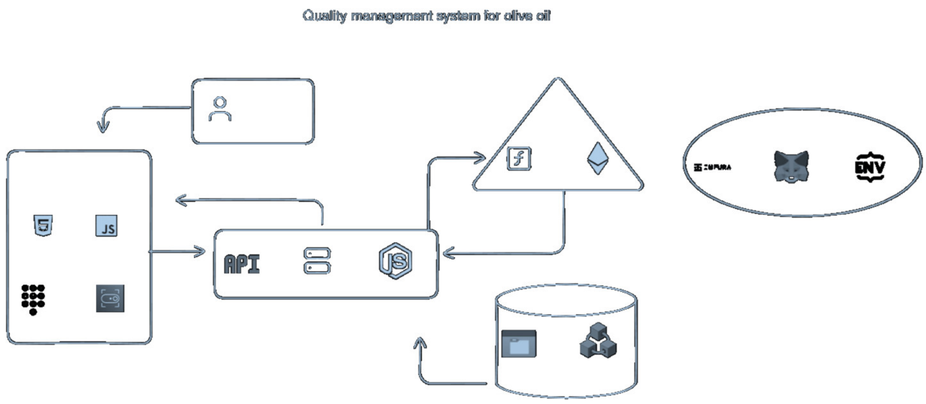

Figure 1. System architecture.

6.3. Smart Contract Implementation

In our implementation, the smart contract, named **NumberChecker**, is written in Solidity and operates on the Ethereum blockchain. It manages and stores olive oil quality data using the **QualityData** struct, which encapsulates key quality parameters such as acidity, polyphenols, vitamin E, pesticides, and the other measurements presented in Section 6.2. This structured approach ensures easy access and efficient management of quality information.

Key functions include:

- **addNumber()**: Adds or updates quality data for an olive oil batch. It accepts multiple parameters representing different quality metrics, creates a **QualityData** object, and maps it to a unique identifier (batch number). This function is important for maintaining data accuracy and traceability.
- **getNumberData()**: Retrieves quality data for a specified batch number. It includes checks to ensure that the data exists (e.g., non-zero acidity), preventing the retrieval of invalid entries.

The Solidity code is compiled using Truffle, which converts it into bytecode for the Ethereum Virtual Machine (EVM) and generates an Application Binary Interface (ABI). The ABI serves as a bridge between the blockchain and the server-side application, facilitating function calls to the smart contract. The contract is deployed to the Sepolia testnet using Truffle, HDWalletProvider, and Infura. Each time the server adds data to the smart contract, it queries the contract address, resulting in a data table similar to Table 2. HDWalletProvider handles transaction signing with private keys, securely managed through an .env file, ensuring cryptographic security and confidentiality.

Table 2. Etherscan search data for our smart contract address (example execution).

Hash	Method	Block	Age	From	To	Value	Txn Fee
0x1745c0292d...	0xdb19338c	5917762	2 mins ago	0x1390528f...92Dd8c1E3	0x865dd686...527032036	0 ETH	0.00074859
0xe034f9c4f99...	0xdb19338c	5917761	2 mins ago	0x1390528f...92Dd8c1E3	0x865dd686...527032036	0 ETH	0.00077232
0xb108196428...	0xdb19338c	5917760	3 mins ago	0x1390528f...92Dd8c1E3	0x865dd686...527032036	0 ETH	0.00072075
0x72c7bdf3078...	0xdb19338c	5917759	3 mins ago	0x1390528f...92Dd8c1E3	0x865dd686...527032036	0 ETH	0.00069147

6.4. Server-Side Implementation

The server, built with Node.js and Express, functions as an intermediary between the client interface and the blockchain. It processes CSV data, communicates with the blockchain to store or retrieve information, and serves web pages to the client.

Key Server Functions include:

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- **processCSV()** : Reads and parses CSV files to extract olive oil quality data, converting and validating data types as needed. It invokes the smart contract's **addNumber()** to record each batch's data on the blockchain.

API Endpoints include:

- **/getData/:number** : Handles requests to retrieve olive oil quality data for a specified batch number, by interacting with the **getNumberData()** function of the smart contract.
- **/checkQuality/:number** : Performs quality checks by retrieving data through **getNumberData()** and evaluating it against predefined quality standards.

API endpoints are tested using Postman to simulate client requests and assess server responses. This ensures that each endpoint handles errors correctly, processes data as expected, and communicates with the blockchain without issues. The server also depicts success and failure console messages when executing, as shown in Figure 2.

Figure 2. Example execution of the server-side software (success message).

6.5. Client-Side Interface

The client interface is developed using HTML, CSS, and JavaScript, providing a user-friendly environment for inputting batch numbers to retrieve information or perform quality checks, as depicted in Figure 3. JavaScript functions, such as **checkQuality()** and **retrieveData()**, are designed to make asynchronous API calls to the server, handle responses, and dynamically update the webpage to display feedback to the user.

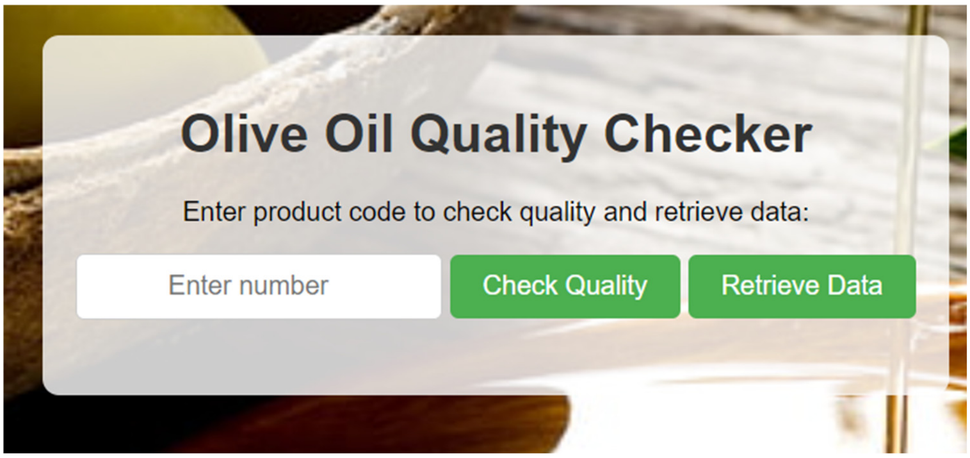

Figure 3. Client-Side User Interface of the Application.

6.6. Future Extensions

The proposed application could be extended to various fields, as illustrated in Figure 4:

Interconnected Smart Contracts: Developing and integrating multiple smart contracts that communicate with each other, with each managing a different aspect of the supply chain, such as

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production, processing, transport, and final distribution. These interconnected contracts would share a common product ID, ensuring seamless data flow across all stages.

Digital Certificates: Creating digital certificates for each stage of the supply chain, registered on the blockchain, to ensure the integrity and continuity of information. These certificates could be issued for specific batch IDs or for an entire product, ensuring transparency and quality assurance throughout the process.

Real-time Data Analysis: Integrating real-time data analysis tools capable of processing large volumes of supply chain data, providing early insights and warnings about potential quality or safety issues.

Use of Decentralized Infrastructure Services: Leverage decentralized hosting services, such as InterPlanetary File System (IPFS), for data storage and distribution, enhancing the security and availability of supply chain information.

User-friendly Platform: Developing a user-friendly platform that enables supply chain stakeholders to easily post, monitor, and verify quality data. The platform can provide support for administrative operations, in order to call specific add and view functions within the smart contracts, simplifying interaction with the system.

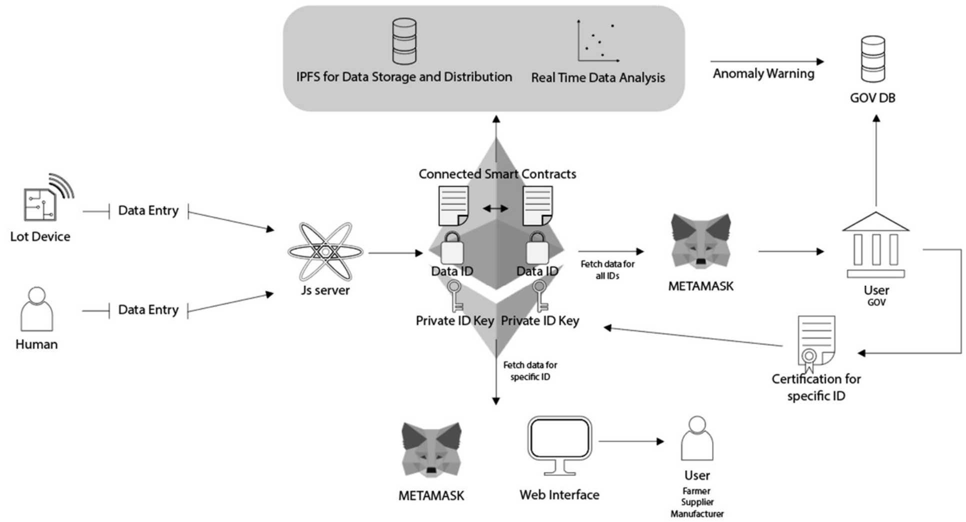

Figure 4. Extended and scalable architecture for a food quality and safety certification application.

7. Conclusions

The integration of blockchain technology into the agri-food supply chain, particularly for olive oil traceability, presents a revolutionary approach to addressing long-standing challenges in food safety, quality assurance, and transparency. By leveraging blockchain's decentralized, immutable ledger and its capacity to work seamlessly with IoT devices, this study demonstrated how food traceability can be drastically improved. Blockchain ensures that every stage of the supply chain, from production to final delivery, is securely recorded, eliminating opportunities for tampering or fraud.

This study developed a practical web application linked to the Ethereum blockchain to monitor olive oil quality using smart contracts. These contracts enhance traceability by recording critical quality metrics, ensuring data integrity, and providing real-time updates across the supply chain. The decentralized nature of the system eliminates reliance on a central authority, which is prone to inefficiencies and vulnerabilities, such as server outages and data breaches.

The research also highlighted several key benefits:

- **Transparency and Trust**: Blockchain allows all participants, including producers, retailers, and consumers, to access real-time, tamper-proof records of the product's journey through the

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supply chain. This transparency fosters trust and confidence [30], especially for high-value products like olive oil, which are frequently targeted by fraud.

- **Enhanced Traceability**: The smart contracts deployed within the system ensure that each batch of olive oil is traceable throughout its lifecycle. This feature is critical in addressing quality concerns and ensuring compliance with safety regulations, offering a more robust mechanism than traditional methods.
- **Automation and Efficiency**: Through smart contracts, the system automates key processes such as quality verification and certification, drastically reducing human error and the need for intermediaries. This reduces operational costs while speeding up decision-making.

Despite the considerable potential of this technology, the research also uncovered several challenges that need to be addressed for widespread adoption. The most significant of these is ensuring that the data inputs—such as laboratory analysis results or sensor readings—are trustworthy and protected from tampering. Additionally, the successful implementation of such systems requires a substantial investment in training stakeholders throughout the supply chain. Without the necessary IT expertise and system familiarity, there may be difficulties in achieving the full potential of blockchain technology in this domain.

Future extensions of this work could involve the integration of more advanced real-time data analysis tools, decentralized storage solutions such as IPFS, and the expansion of the system to cover other stages of the supply chain, from production to retail. Additionally, the use of more interconnected smart contracts could allow for a more holistic and granular view of the supply chain, further enhancing traceability and quality assurance.

In conclusion, while challenges remain, the blockchain and IoT-powered approach to food traceability offers a transformative solution for the agri-food industry. With proper investment and development, this technology can ensure that consumers receive high-quality, safe products while producers benefit from increased trust and market confidence. The system outlined in this study provides a foundation for future innovation and development in the secure, transparent management of food supply chains.

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