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Blockchain-Backed Sustainable Management of Italian Tomato Processing Industry

Sajid Safeer [1,*] and Cataldo Pulvento [2]

[1] International School of Advanced Studies, University of Camerino, 62032 Camerino, Italy
[2] Department of Soil, Food and Plant Sciences, University of Bari Aldo Moro, 70126 Bari, Italy; cataldo.pulvento@uniba.it
* Correspondence: sajid.safeer@unicam.it

Abstract: This study addresses significant concerns highlighted by the European Parliament regarding the decline of the Italian tomato processing industry, which possess a threat to Italy's culinary heritage and global market position. This research offers a solution that leverages blockchain technology to enhance transparency, traceability and operational efficiency within the tomato supply chain. By integrating Solidity, Remix IDE, MetaMask wallet and Sepolia Testnet, our proposed model establishes a robust blockchain-based smart-contract system. This system actively engages cultivators, wholesalers, retailers and end-users facilitating seamless real-time updates across the entire supply chain. Implementing this model in key tomato-producing regions such as Apulia, utilizing platforms like Mainnet or Hyperledger Fabric, aims to stabilize the industry. Furthermore, this study promotes automating smart contracts, integrating IoT devices and developing decentralized applications (DApps). This strategy ensures transparency for end-users, enhances organic food availability and mitigates contamination risks. This study also recommends government involvement to upgrade transportation and storage facilities, aiming to reduce post-harvest losses. This research establishes the groundwork for the sustainable management of the Italian tomato processing industry.

Keywords: blockchain; tomato industry; supply chain; sustainability; smart contract

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1. Introduction

1.1. Justification for the Selection of the Research Area

A supply chain is a complex network involving various entities, groups, resources, actions and technologies that collaboratively work towards the manufacturing and sale of a specific product. It encompasses the seamless flow of raw materials from producers to processors, sellers and ultimately end-users [1]. The agricultural food supply chain (AFSC) is a specialized system that focuses on the production and distribution of agricultural products to end-users through various stages. It is an integrated framework that includes food production, processing, delivery and consumption, often referred to as "seed to deal". The term AFSC is widely used in diverse agricultural disciplines, including agronomy, agro-food, agriculture science and agri-business and management [2].

In today's global economy, agricultural goods, especially those derived from crops such as food and biofuel, play a significant role [3]. Consumers of agricultural products are increasingly seeking information beyond supermarket availability, including details about the product's farming, advertising, supply, shipping and processing actions. This consumer attitude is closely linked to public health concerns arising from instances of severe contamination. As a result, communities are becoming more vigilant and conscious about the accessibility, toxicity and safety of the foods they consume [4].

The enforcement of the AFSC is not only essential for ensuring a reliable and safe food supply but also for promoting economic progress, eco-friendly sustainability and waste reduction and fostering innovation. The efficiency and effectiveness of the AFSC play a key role in addressing various emerging global challenges [5]. However, the existing AFSC faces several issues, including the increasing demand for food products and end-user preferences for safety. Stricter regulations, security concerns and the need for traceability compel directors, manufacturing units, industries and experts involved in the AFSC to adopt new approaches, tools and techniques to address current food supply chain concerns and design the network accordingly [6].

To enhance the performance of the AFSC, each participant in the supply chain must be capable of organizing its individual activities. This allows every party involved to receive appropriate benefits based on negotiations made during the coordination process [7]. Given the vital significance of the AFSC to food security, quality, food system resilience and agricultural development, research in this area is rapidly evolving. Many efforts have focused on specific aspects of the supply chain, such as traceability, tracking, managing and decision-making [8]. However, there is limited scientific literature addressing the fresh crop supply chain. Cultivable products are particularly sensitive to time and temperature, with brokers often acting as the price deciders, resulting in decreased rewards for growers as intermediaries' profits increase. Additionally, there is a lack of proper tracking of agri-food throughout the transportation journey [9].

1.2. Unfair Trade Practices

The introduction of tomatoes to Italy in the 1500s marked the beginning of their extensive usage in the Italian kitchen, a trend that gained momentum during the 19th century [10]. In 2022, Italy's tomato production, as reported by the U.S. Department of Agriculture (2023), reached 5.5 million metric tons (MMTs), reflecting a 10% decrease compared to the previous year. This decline is attributed to an 8.5% reduction in cultivated area, prompting the country to import 17,069 metric tons of processed tomatoes in 2022 [11]. Alessandro Squeri, the Director General of Steriltom, a renowned Italian tomato production firm, expresses reservations about these statistics. He contends that, beyond weather-related setbacks and unfair foreign trade practices, several internally manageable factors significantly contributed to the reduction in cultivated hectares and a subsequent decline in productivity [12].

One pressing issue revolves around the lack of traceability and control in the tomato supply chain. Large-scale dealers wield considerable influence over the prices of both raw resources and processed products. More than 8000 Italian farmers have voiced their concerns, indicating that the rates fixed for tomatoes in the 2021 marketing year failed to cover production costs. This means that 115 Italian canning corporations often sold tomatoes at prices lower than the actual cost of production. In 2021, a member of the European Parliament raised a question and requested the commission's immediate intervention to safeguard the endangered Italian tomato industry. This situation highlights the urgency of addressing internal challenges to secure the sustainability of Italy's tomato production, a vital aspect of the country's culinary heritage [13].

1.3. Related Work

In the contemporary world, food security has become a paramount concern for both profitable enterprises and essential services [14]. However, the majority of existing solutions are centralized, leading to significant operational challenges. To comprehensively understand the dynamics within and between AFSC fields, a literature review was conducted as performed by [15]. This assessment has highlighted the potential benefits of blockchain technology in enhancing traceability and information security within the AFSC.

According to [16], efficient management of the agri-food supply chain, aligned with consumer expectations, requires unanimous agreement among all participants regarding the details documented on the blockchain. This includes information from raw ingredients to finished products, contributing to the enhancement of an enterprise's image, fostering trust among existing users and ensuring food safety. The existing literature on agri-food has explored the advantages of blockchain technology, yet empirical evidence and convincing experimental practices remain limited [17]. These benefits encompass various aspects, such as supply chain organization, food safety and economic outcomes for companies.

Dutta and his colleague's emphasize the significance of blockchain technology in reducing food wastage, expediting logistic processes and providing direct details to consumers [18]. Tian discusses the potential to link dairy product information to the blockchain to efficiently manage security and quality concerns [19]. Additionally, Anastasiadis and colleagues discovered, during an exploration of a sustainable tomato supply chain, that health, trust, quality, nutrition and safety-related values are crucial for consumers in accepting a blockchain traceability system [20].

Despite these promising findings, many stakeholders are unprepared for a full transition to blockchain due to insufficient information and understanding of the technology and its financial benefits [21]. Sellers show minimal engagement with blockchain due to a lack of familiarity with its economic benefits. There is a notable lack of experiential proof evaluating the impact of this novel technology on the cost-effective performance of agri-food supply chains (AFSCs) [22]. Forty-nine global blockchain projects in the agri-food sector have been identified so far, with only four fully integrating blockchain technology, while the rest remain experimental or are used for visibility purposes [23].

Implementing a blockchain-based smart contract system in the Italian tomato processing industry faces several challenges. Integrating blockchain with existing systems, managing large data volumes while ensuring privacy and resistance to new technology among stakeholders are significant issues [24]. Additionally, regulatory compliance, high setup costs, ensuring interoperability between different blockchain platforms and addressing the environmental concerns of energy-intensive systems further complicate adoption [25]. Practical challenges include deploying IoT devices in rural areas and designing user-friendly interfaces for all stakeholders [26]. Despite these challenges, proper training, regulatory frameworks and stakeholder collaboration can help realize the benefits of blockchain in enhancing transparency, traceability and efficiency in the supply chain.

1.4. Motivation and Objectives

Tomato cultivation in Italy is predominantly centered in the central–southern provinces and the northern districts, with Apulia, especially the Foggia province, playing a significant role in annual production. This research aims to propose an integrated model for sustainably incorporating blockchain technology into the current tomato supply chain.

Blockchain can revolutionize the Italian tomato processing industry by creating a transparent, traceable and efficient supply chain from farm to table. This technology ensures the verification of organic practices, reduces food fraud and promotes fair trade practices. By minimizing post-harvest losses through better coordination and reducing reliance on intermediaries, blockchain enhances efficiency and promotes environmental sustainability. Additionally, it supports better inventory management and waste reduction, contributing to a more sustainable and resilient tomato industry.

The research is driven by the need to respond to inquiries from the European Parliament. It aims to enhance the efficiency and sustainability of the tomato supply chain and position blockchain technology as a transformative catalyst for addressing cost and price concerns for farmers. By integrating sustainable blockchain solutions, the study envisions establishing a more resilient and transparent tomato supply chain in Foggia, setting a precedent for other agricultural regions seeking innovative approaches. This sustainable approach not only ensures economic benefits but also supports environmental conservation, aligning with global efforts to promote sustainable agricultural practices.

2. Materials and Methods

2.1. Proposed Infrastructure

In this contemporary research endeavor, a blockchain, established on the Sepolia Testnet, is presented for the tomato supply chain in the Apulia region, Italy. The development of this innovative system involved the utilization of four fundamental tools: the

Solidity programming language, the Remix Integrated Development Environment (IDE), the MetaMask wallet and the Sepolia Testnet, ensuring the seamless execution of the entire procedure [27] (Figure 1).

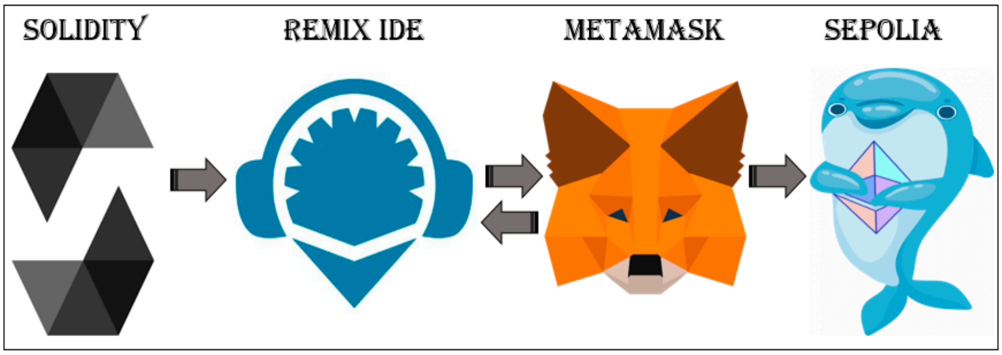

Figure 1. Four pillars of innovation—Solidity, Remix IDE, MetaMask and Sepolia Testnet.

2.2. Solidity Programming Language

According to Antonopoulos and Wood, Solidity is primarily a statistics-involved programming language designed for the development and implementation of smart contracts on various public or private blockchain setups, with a particular emphasis on the Ethereum platform [28]. UK born Ethereum cofounder Gavin Wood first introduced Solidity in 2014, and its developmental prospects were subsequently assessed by a team led by Christian Reitwiessner and Alex Beregszaszi. Programs written in Solidity can run on the Ethereum Virtual Machine (EVM), the Compatible Virtual Machine (CVM) or both. For the purposes of this research work, Solidity version ˆ0.8.0 was utilized.

2.3. Remix Integrated Development Environment (IDE)

Remix, an online IDE, serves as a robust toolset encapsulating the functionalities of a web application and was utilized in this project. This influential and user-friendly developmental interface plays a pivotal role in facilitating the writing, debugging, testing, compiling and deploying of smart contracts compatible with both the EVM and CVM. It stands out as the preferred choice among developers due to its open-source nature, free accessibility, lack of specific setup requirements and the provision of a flexible online coding environment [29].

2.4. MetaMask Wallet

MetaMask 11.5.1 is primarily a software application developed by ConsenSys Software Inc. (Fort Worth, TX, USA), designed to seamlessly interact with the blockchain ecosystem. This versatile tool allows users to access their Ethereum wallet through a browser extension or mobile application. The MetaMask wallet serves as a centralized hub for managing account keys, recording transactions, sending or receiving cryptocurrencies and engaging with DApps [30]. In the context of this research project, the MetaMask wallet version 11.5.1 played a crucial role in facilitating various interactions within the blockchain network.

2.5. Sepolia Testnet

The term "Ethereum Mainnet" refers specifically to the genuine Bitcoin blockchain and network, distinguishing it from test-net, sig-net and reg-test networks [31]. In contrast to these, smart contracts executed on the Ethereum Mainnet involve real cryptocurrency transactions that carry monetary value, representing actual assets. On the other hand, "Ethereum Testnets" are integral components of the blockchain environment designed to enable developers to test and deploy smart contracts and DApps without utilizing real Ether (ETH) [32]. In this capacity, testnet tokens, devoid of monetary worth, provide a secure and risk-free platform for experimentation and innovation.

During the latter half of 2021, Ethereum developers introduced "Sepolia" as a proof-of-authority testnet, recommending it as the default testnet for smart contract application development [33]. In the current study, the Sepolia testnet has been employed, providing a reliable and controlled environment for testing and refining the blockchain-based applications under investigation.

3. Results

3.1. Working Environment

To assess the efficacy of the proposed system, a performance evaluation was conducted. In the suggested tomato supply chain, there are four essential participants who play crucial roles in its functioning. Firstly, we have the cultivator, responsible for growing and nurturing the tomatoes from the initial stages. The wholesaler steps in next, acting as a bridge between the cultivator and retailer by handling bulk quantities of tomatoes. The retailer takes charge of bringing the tomatoes to the end-users, operating at a more localized level and making the produce accessible to end-users. Finally, the end-user completes the chain by purchasing and utilizing the tomatoes (Figure 2).

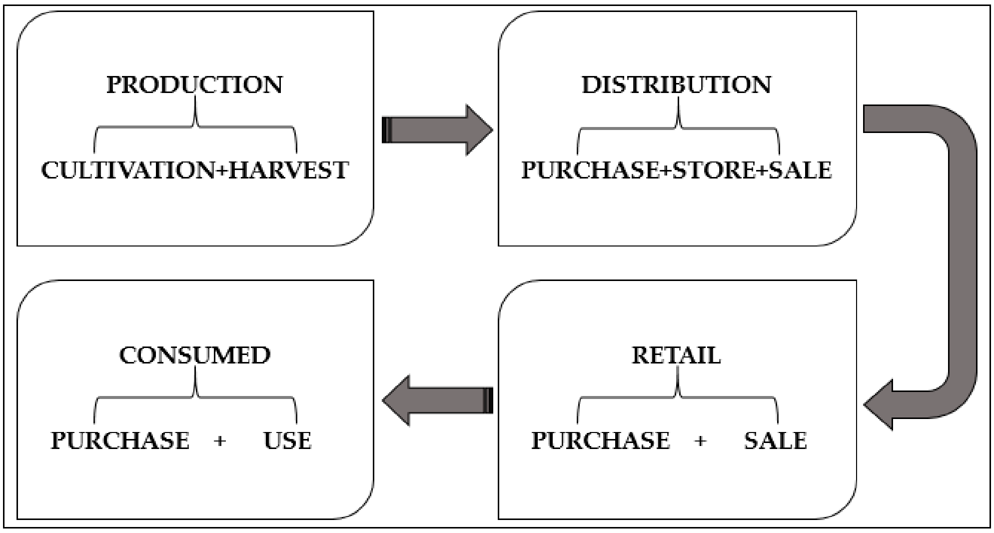

Figure 2. Illuminating the dynamics—the holistic operation of the tomato supply chain.

3.2. Smart Contract Symphony

The creation and deployment of the smart contract for the proposed tomato supply chain were executed using the Remix IDE platform. Specifically, the compiler version 0.8.22+commit.4fc1097e within the Remix IDE environment was employed for this purpose. To facilitate deployment, the Sepolia Testnet was integrated into our MetaMask wallet. It is noteworthy that, by default, Sepolia test ethers were automatically added to our wallet upon entering the Sepolia testnet environment.

To emulate various stakeholders within the tomato supply chain, we established four distinct accounts within the MetaMask environment, representing cultivator, wholesaler, retailer and end-user roles. Each account was endowed with Sepolia test ethers, as depicted in Figures 3 and 4.

3.3. MetaMask Wallet Innovative Integration

Subsequently, we seamlessly connected our Remix IDE-generated Solidity smart contract with the MetaMask wallet. This connection was established by selecting the "Injected-provider MetaMask" option under the "Environment" tab within the Remix IDE. The successful integration is illustrated in Figure 5, demonstrating the connectivity between our MetaMask wallet and the Remix IDE platform. This strategic linkage facilitates the seamless execution and interaction of the smart contract within the proposed tomato supply chain. Additionally, we have implemented specific limits on Gas usage for optimized performance.

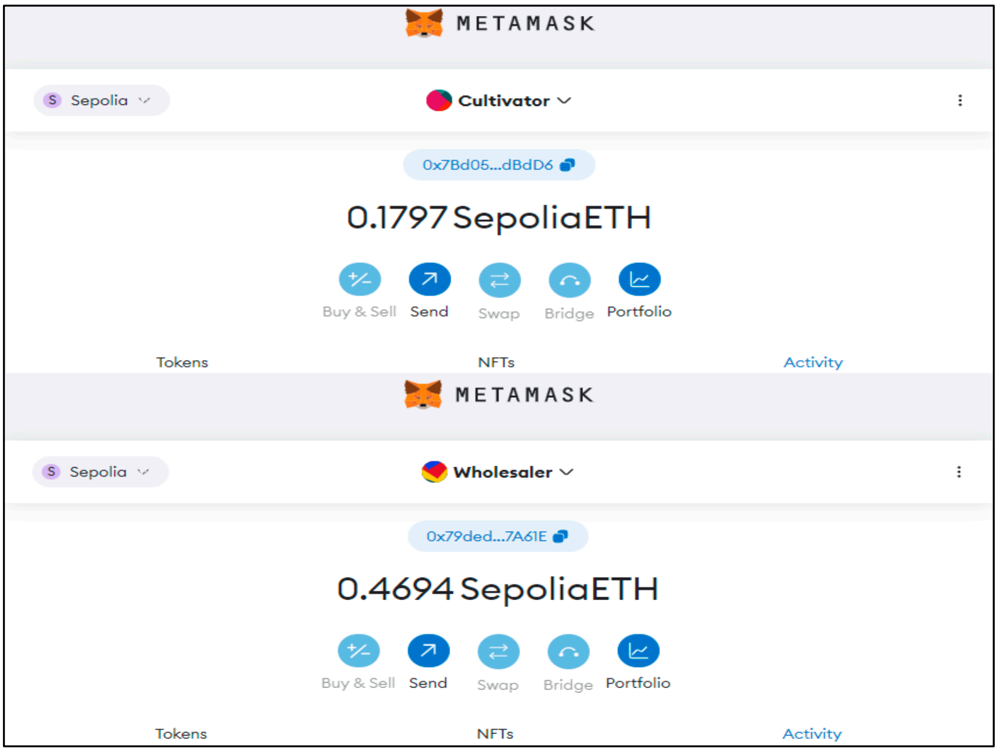

Figure 3. MetaMask wallets at the cultivator and wholesaler nexus.

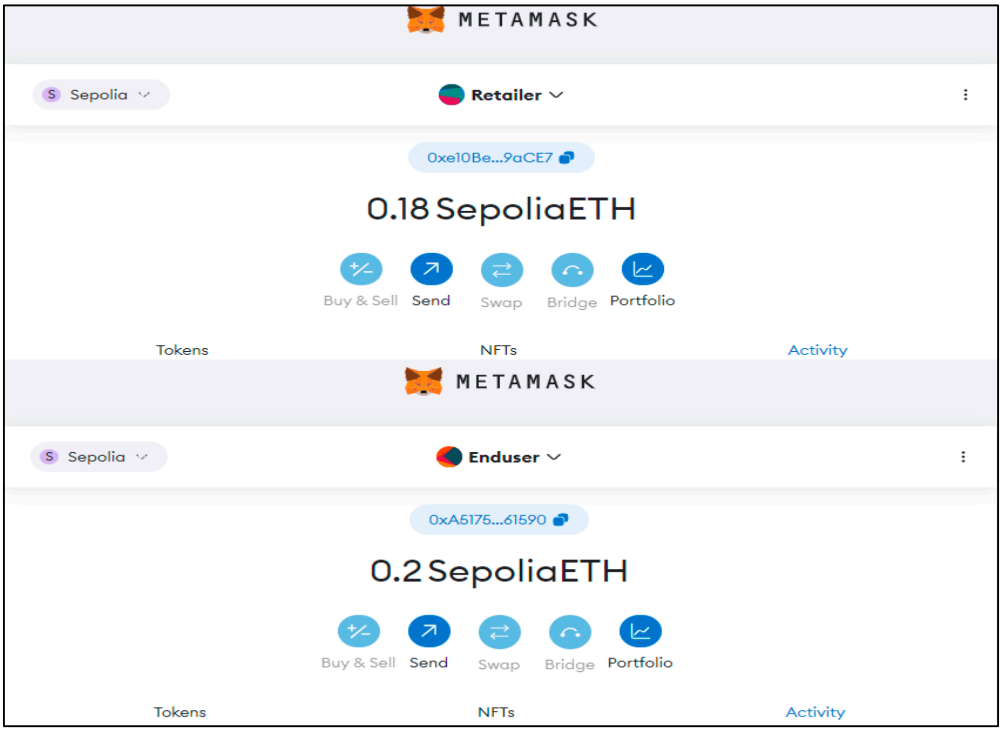

Figure 4. MetaMask wallets at the retailer and end-user nexus.

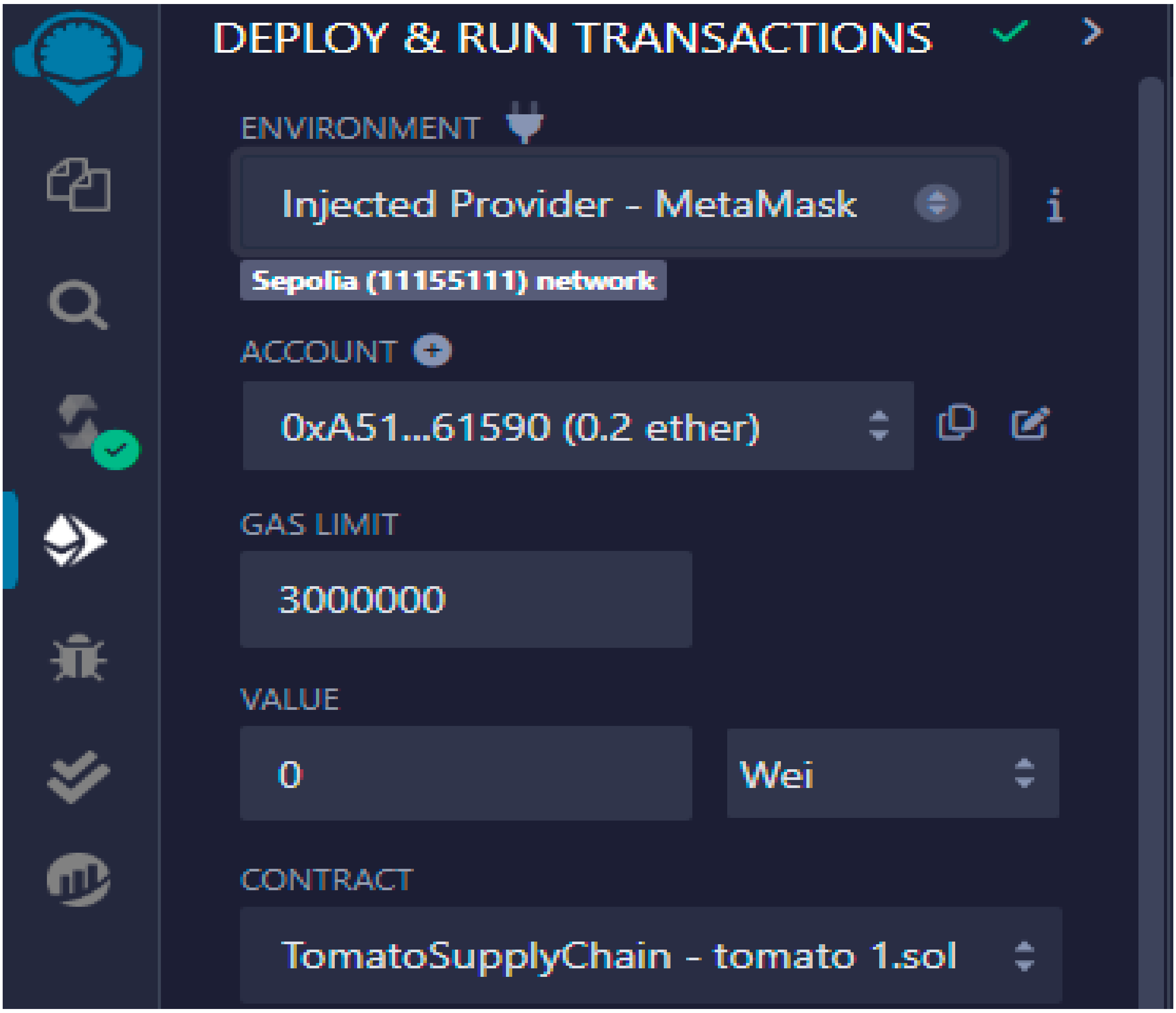

Figure 5. Strategic integration between MetaMask and Remix IDE.

3.4. Smart Contract Deployment

3.4.1. Initiating Interactive Pop-Ups

Each participant in the Solidity smart contract played a crucial role in its deployment, tailoring each part according to individual requirements using their specific MetaMask account addresses and calling functions associated with their role. The deployment process began with the cultivator taking ownership of the smart contract. Utilizing their MetaMask wallet's "cultivator account", they deployed the contract, triggering various pop-ups (Figure 6).

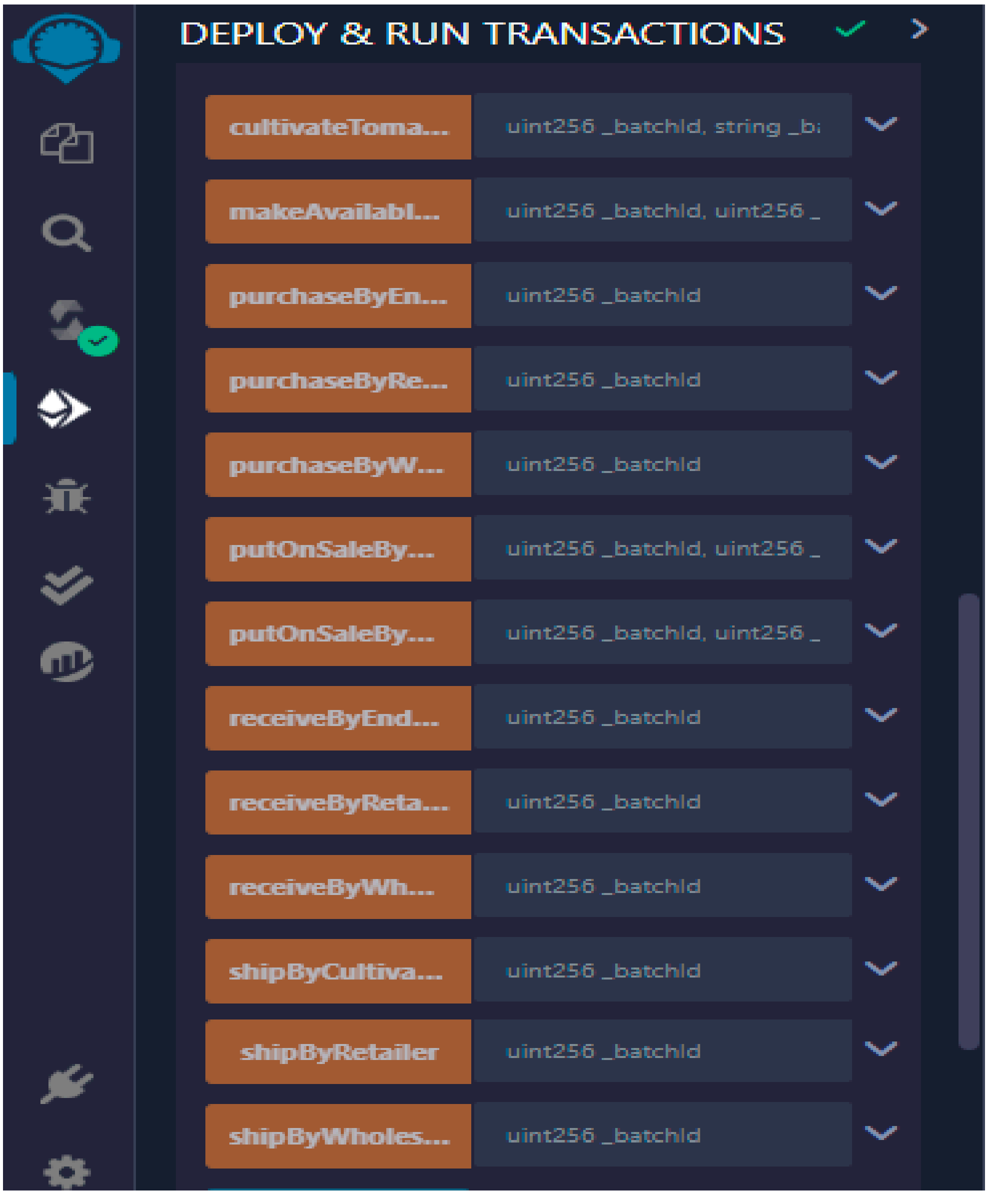

Figure 6. Smart contract deployment unveiled—initiating interactive pop-ups.

3.4.2. Theme of Smart Contract Functions

Cultivation Phase

In the proposed tomato supply chain, the journey of a tomato batch begins with the cultivation phase. The cultivator, the initial owner of the tomatoes, interacts with the smart contract to cultivate a new batch. The "cultivateTomatoes" function is called, which initializes a new entry in the mapping for the batch, recording essential details such as batch code, name, quantity, price and harvest timestamp. The cultivator becomes the owner of this batch.

```
function cultivateTomatoes(uint256 _batchId, string memory _batchCode, string memory _name, uint256 _quantitykg,
    uint256 _priceperkg, string memory _harvestTimestamp) public onlyOwner {
    tomatoBatches[_batchId] = TomatoBatch(_batchId, _batchCode, _name, _quantitykg, _priceperkg, _harvestTimestamp,
    Stage.Cultivation, owner);
    emit StageChanged(_batchId, Stage.Cultivation);
}
```

Available for Sale

When the crop reaches maturity and is ready for harvest, the cultivator initiates the "makeAvailableForSale" function. This pivotal step signals the transition of the tomatoes stage to available for sale. Through this function, the cultivator seamlessly updates the smart contract, making the freshly harvested tomatoes accessible for purchase by other participants in the supply chain. The "makeAvailableForSale" function underscores the smart contract's role in automating and facilitating the progression of the tomatoes from the cultivation phase to the market, ensuring a transparent and efficient supply chain process.

```
function makeAvailableForSale(uint256 _batchId, uint256 _price) public onlyOwner {
    TomatoBatch storage tomato = tomatoBatches[_batchId];
    require(tomato.stage == Stage.Cultivation, "Tomatoes must be cultivated");
    tomato.stage = Stage.AvailableForSale;
    tomato.price = _price;
    emit StageChanged(_batchId, Stage.AvailableForSale);
}
```

Purchase by Wholesaler

When a distributor desires a specific tomato batch, they invoke the "purchaseByWholesaler" function. This action not only facilitates the purchase but also seamlessly transfers ownership to the distributor. Importantly, payment is executed during this transaction, ensuring a transparent and secure exchange of funds. The "purchaseByWholesaler" function exemplifies the smart contract's capability to streamline transactions between stakeholders, fostering trust and efficiency within the proposed tomato supply chain.

```
function purchaseByWholesaler(uint256 _batchId) public onlyOwner {
    TomatoBatch storage tomato = tomatoBatches[_batchId];
    require(tomato.stage == Stage.AvailableForSale, "Tomatoes must be available for sale");
    tomato.stage = Stage.PurchasedByWholesaler;
    tomato.ownerAddress = msg.sender;
    emit StageChanged(_batchId, Stage.PurchasedByWholesaler);
}
```

Shipment and Receipt by Wholesaler

After the tomatoes are made available for sale, the next step in the tomato supply chain involves their shipment to the wholesaler. The cultivator, utilizing the "shipByCultivator" function, initiates the transportation process, updating the smart contract with the shipping details. Subsequently, the wholesaler acknowledges the receipt of the tomatoes by triggering the "receiveByWholesaler" function. This dynamic interaction between the cultivator and the wholesaler not only signifies the physical movement of the produce but also ensures a synchronized and transparent record-keeping within the blockchain-based supply chain system, enhancing accountability and traceability.

```
function shipByCultivator(uint256 _batchId) public onlyOwner {
    TomatoBatch storage tomato = tomatoBatches[_batchId];
    require(tomato.stage == Stage.PurchasedByWholesaler, "Tomatoes must be purchased by wholesaler");
    tomato.stage = Stage.ShippedByCultivator;
    emit StageChanged(_batchId, Stage.ShippedByCultivator);
}

function receiveByWholesaler(uint256 _batchId) public onlyOwner {
    TomatoBatch storage tomato = tomatoBatches[_batchId];
    require(tomato.stage == Stage.ShippedByCultivator, "Tomatoes must be shipped by cultivator");
    tomato.stage = Stage.ReceivedByWholesaler;
    emit StageChanged(_batchId, Stage.ReceivedByWholesaler);
}
```

Sale by Wholesaler

Upon receiving the tomato batches, the wholesaler plays a crucial role in the supply chain by making them available for sale to retailers. This pivotal step is executed through the "putOnSaleByWholesaler" function, where the wholesaler specifies the pricing details for the tomatoes. By invoking this function, the wholesaler not only establishes the retail value but also initiates the integration of these tomatoes into the broader market. The transparency and automation inherent in the smart contract enable an efficient and traceable process, ensuring that the tomatoes are seamlessly transitioned from the wholesaler to the retail stage with defined pricing parameters.

```
function putOnSaleByWholesaler(uint256 _batchId, uint256 _price) public onlyOwner {
    TomatoBatch storage tomato = tomatoBatches[_batchId];
    require(tomato.stage == Stage.ReceivedByWholesaler, "Tomatoes must be received by wholesaler");
    tomato.stage = Stage.PutOnSaleByWholesaler;
    tomato.price = _price;
    emit StageChanged(_batchId, Stage.PutOnSaleByWholesaler);
}
```

Purchase by Retailer

Upon deciding to procure tomatoes for their retail offering, a retailer engages in the supply chain dynamics by invoking the "purchaseByRetailer" function. This transaction facilitates the seamless transfer of ownership from the wholesaler to the retailer, marking a critical transition in the tomato's journey. The retailer, now the rightful owner, fulfills the payment obligation to the wholesaler, solidifying the commercial aspect of the deal.

```
function purchaseByRetailer(uint256 _batchId) public onlyOwner {
    TomatoBatch storage tomato = tomatoBatches[_batchId];
    require(tomato.stage == Stage.PutOnSaleByWholesaler, "Tomatoes must be put on sale by wholesaler");
    tomato.stage = Stage.PurchasedByRetailer;
    tomato.ownerAddress = msg.sender;
    emit StageChanged(_batchId, Stage.PurchasedByRetailer);
}
```

Shipment and Receipt by Retailer

In a parallel fashion to the shipment protocol with the wholesaler, the tomato supply chain advances as the wholesaler ships the tomatoes, and the retailer acknowledges receipt. This logistical handover, executed through the "shipByWholesaler" and "receiveByRetailer" functions, cements the tomatoes' physical transition from one node of the supply chain to the next.

```
function shipByWholesaler(uint256 _batchId) public onlyOwner {
    TomatoBatch storage tomato = tomatoBatches[_batchId];
    require(tomato.stage == Stage.PurchasedByRetailer, "Tomatoes must be purchased by retailer");
    tomato.stage = Stage.ShippedByWholesaler;
    emit StageChanged(_batchId, Stage.ShippedByWholesaler);
}

function receiveByRetailer(uint256 _batchId) public onlyOwner {
    TomatoBatch storage tomato = tomatoBatches[_batchId];
    require(tomato.stage == Stage.ShippedByWholesaler, "Tomatoes must be shipped by wholesaler to retailer");
    tomato.stage = Stage.ReceivedByRetailer;
    emit StageChanged(_batchId, Stage.ReceivedByRetailer);
}
```

Sale by Retailer

Empowered by the "putOnSaleByRetailer" function, the retailer unveils the tomatoes for potential end-users. This strategic move places the tomatoes on the market, allowing consumers to initiate transactions and acquire ownership. The associated price, set by the retailer, further shapes the dynamics of the purchasing process, and the smart contract meticulously manages the transition, recording each stage for clarity and accountability within the tomato supply chain.

```
function putOnSaleByRetailer(uint256 _batchId, uint256 _price) public onlyOwner {
    TomatoBatch storage tomato = tomatoBatches[_batchId];
    require(tomato.stage == Stage.ReceivedByRetailer, "Tomatoes must be received by retailer");
    tomato.stage = Stage.PutOnSaleByRetailer;
    tomato.price = _price;
    emit StageChanged(_batchId, Stage.PutOnSaleByRetailer);
}
```

Purchase by End-User

As the end-user finds the desired tomatoes, the "purchaseByEnduser" function is invoked, facilitating the transfer of ownership. The end-user emerges as the new custodian of the tomatoes, solidifying the transaction, and the corresponding payment is seamlessly directed to the retailer. This crucial step in the supply chain ensures a smooth and transparent transition of ownership from retailer to end-user, further reinforcing the integrity of the tomato supply chain smart contract.

```
function purchaseByEnduser(uint256 _batchId) public onlyOwner {
    TomatoBatch storage tomato = tomatoBatches[_batchId];
    require(tomato.stage == Stage.PutOnSaleByRetailer, "Tomatoes must be put on sale by retailer");
    tomato.stage = Stage.PurchasedByEnduser;
    tomato.ownerAddress = msg.sender;
    emit StageChanged(_batchId, Stage.PurchasedByEnduser);
}
```

Shipment and Receipt by End-User

Following the purchase by the end-user, the retailer takes the initiative to ship the tomatoes through the "shipByRetailer" function. Subsequently, the end-user acknowledges the receipt of the tomatoes, completing the final leg of the supply chain by performing "recdiveByEnduser" function. This streamlined process ensures a secure and traceable delivery, reinforcing the transparency embedded in the tomato supply chain smart contract.

```
function shipByRetailer(uint256 _batchId) public onlyOwner {
    TomatoBatch storage tomato = tomatoBatches[_batchId];
    require(tomato.stage == Stage.PurchasedByEnduser, "Tomatoes must be purchased by enduser");
    tomato.stage = Stage.ShippedByRetailer;
    emit StageChanged(_batchId, Stage.ShippedByRetailer);
}

function receiveByEnduser(uint256 _batchId) public onlyOwner {
    TomatoBatch storage tomato = tomatoBatches[_batchId];
    require(tomato.stage == Stage.ShippedByRetailer, "Tomatoes must be shipped by retailer to enduser");
    tomato.stage = Stage.ReceivedByEnduser;
    emit StageChanged(_batchId, Stage.ReceivedByEnduser);
}
```

4. Discussion

In recent years, the Italian tomato processing industry has confronted a notable decline in production, grappling with a myriad of internal and external challenges. Internally, issues such as the absence of traceability and control within the supply chain, coupled with pricing intricacies, have surfaced as substantial threats to the sustainability of tomato cultivation in the country. This dire circumstance is further compounded by the stark incongruity between production costs and selling prices and import invasion, compelling intervention from the European Parliament. In response to these multifaceted challenges, this research initiative was launched with the objective of formulating a viable solution to safeguard the endangered tomato processing industry of Italy, a sector representing approximately 15% of global production and 56% of the European crop [12].

This blockchain-based smart contract system actively involves cultivators, wholesalers, retailers and end-users, ensuring transparency and traceability throughout the supply chain.

Cultivators play a crucial role by updating the blockchain with real-time information, such as harvesting timestamps, thereby benefiting all participants by eliminating the need for intermediaries. This reduction in intermediaries not only streamlines the supply chain but also significantly lowers transaction costs, making the system highly cost-effective. The automation of processes through smart contracts reduces administrative overhead and minimizes human error, further cutting operational expenses. In cases where direct transactions with retailers or end-users are impractical, cultivators have the option to sell their produce to wholesalers based on market demand, enhancing market efficiency and economic benefits [34–36]. Overall, the cost-effectiveness of this blockchain-based system contributes to its sustainability and scalability, providing a model that can be adapted to other agricultural sectors.

Our proposed system improves transparency and security for all stakeholders in the supply chain through the use of blockchain technology. This technology maintains an unchangeable record of all transactions, accessible to all participants. Smart contracts automate processes, enhancing transparency and reducing the potential for fraud. Furthermore, cryptographic methods are employed to protect the integrity and confidentiality of data. The system ensures privacy by using data encryption, limiting access permissions to authorized parties, and employing zero-knowledge proofs for transaction validation without revealing sensitive information [37]. The proposed blockchain model is designed to be scalable and adaptable, making it suitable for both small-scale and large-scale farmers. This flexibility ensures that even small farmers can benefit from the system's transparency and efficiency, while larger operations can leverage its robustness to manage complex supply chains. The cost-effectiveness and ease of implementation make this model accessible to a wide range of agricultural enterprises.

The perishable nature of tomatoes contributes to a significant portion of the crop going to waste post-harvest due to insufficient transportation and storage facilities. Government involvements providing these essential facilities can effectively mitigate post-harvest losses, fostering benefits for farmers and stimulating increased tomato availability. Furthermore, the integration of Internet of Things (IoT) devices into the proposed system holds the potential to elevate productivity. Addressing concerns raised by the European Parliament, implementing the proposed infrastructure with the Mainnet or Hyperledger Fabric across tomato-producing regions like Apulia can alleviate uncertainties for farmers and potentially boosting cultivation. Additionally, the implementation of a private blockchain for tax management, coupled with low gas fees, stands as a potential contributor to enhanced GDP [38].

This study serves as a foundational framework for digitalizing food supply chains, not only for sustainable management of the Italian tomato processing industry but also for inspiring future research initiatives. Researchers can explore new strategies, especially in smart contract automation and DApp development, building upon the foundations set by this tomato supply chain model. This creates opportunities for innovative solutions and ongoing enhancements in securing and improving global food supply chains [39–41].

5. Conclusions

In conclusion, this research addresses critical challenges within the endangered Italian tomato processing industry. The proposed blockchain-based model ensures transparency and traceability, marking a significant advancement in sustainable tomato supply chain management. By automating smart contracts, it empowers end-users with reliable information to enhance organic food availability and mitigate contamination risks. Stakeholder participation, IoT integration and the utilization of platforms like Mainnet or Hyperledger Fabric across strategic regions are pivotal in reducing post-harvest losses. Government subsidies for modern storage facilities, investments in efficient transportation infrastructure and incentives for adopting advanced logistics technologies further optimize the supply chain. This model not only sets a cornerstone for future research in smart contract automation and decentralized applications but also fosters innovative solutions for continuous improvement in global food supply chains.

Author Contributions: S.S. and C.P.: Methodology, S.S.; Software, S.S.; Validation, S.S.; Writing—original draft, S.S.; Writing—review & editing, S.S. and C.P.; Supervision, C.P.; Project administration, C.P.; Resources, C.P.; Funding acquisition, C.P. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data supporting the findings of this study are available within the article. Additional data can be provided by the corresponding author upon reasonable request.

Conflicts of Interest: This research was conducted by Sajid Safeer under the supervision of Cataldo Pulvento and the authors declare no conflicts of interest.

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