Blockchain and IoT in real time monitoring and transparent traceability of perishable horticultural supply chains

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Abstract:
Perishable crops like tomatoes are very susceptible to quality loss in case of post-harvest handling, mainly because of the absence of real time visibility in the supply chain. This paper introduces the deployment and the evaluation of an integrated system of IoT-based environmental monitoring and blockchain in order to enhance the supply chains of tomatoes in Brazil and Italy, addressing both traceability and quality assurance. The system also recorded real-time temperature and humidity during transport and irreversibly documented the events of critical supplies using Ethereum based smart contracts. The overall field implementation in 14 farms and 3 distribution centers resulted in the decrease of the spoilage by 34 percent, the improvement of the quality tracking and verification speed, and the enhancement of consumer confidence provided by QR-related history of products. The study shows that it is possible to use the combination of blockchain and IoT and create new generation agri-supply chains that would take transparency, efficiency and sustainability in the realm of food safety and quality assurance and consumer trust in perishable product management to new levels.
Keywords: ***Blockchain, IoT, Supply Chain, Perishable products, Traceability, Quality assurance, Agri-Digitalization***

1. Introduction

1.1 Quality Assurance and Transparency Quality Assurance and transparency are important challenges in perishable horticultural chains.

Fruits, vegetables, and herbs are perishable horticultural products, and their post-harvest process of farm-to-consumer quality and safety is greatly challenged. The quality of a product during transportation, storage and handling is very essential because they are sensitive to factors of the environment such as temperature and humidity. Traditional supply chains, however, are usually missing that level of real-time transparency and traceability, losing rather than increasing the quality and spoiling the food. This invisibility is worsened by the fact that the global supply chains are complex and fragmented whereby goods pass through different hands, both farmed and warehouses, distribution centres and retail stores, before becoming visible to the consumer.

In addition, no uniformity in environmental conditions observation practices in transport and storage leads to unstable quality of product. In the lack of data tracking it becomes hard to trace where quality defects occur and consumer is usually left without knowing the route of their produce. Such difficulties indicate the necessity in the development of quick solutions to increase accountability, traceability, and quality assurance across the whole chain of supply.(1)

1.2 Real-Time Monitoring and Traceability requirement in Supply Chains

The need is urgent to install the systems of real-time monitoring, able to monitor the critical variables of the environment (the temperature, the humidity, the geographical position) during the chain of the distribution of perishable products. The prevention is possible because real-time monitoring helps to take actions proactively to prevent spoilage, including the condition of the transport or redirecting the shipment to proper storage. By way of example, being able to know that a product is subjected to unfavorable conditions would enable operators of the supply chain to intervene in such cases, as early as possible, and its possible harmful effects reduced.

The traceability is also equally important in the safety and quality of products. Being able to know where food comes, how it has been treated or processed, and how well it matches some expected quality criteria, not only creates a sense of trust, but also improves the level of food safety by offering an efficient response mechanism to such problems as contamination or recall. In a current climate of food security and growing interest in sustainability in general, there is no higher demand than that of trustworthiness, transparency and responsibility of food systems. Most of this openness and security disappears without the capability to track perishable products in real-time.

1.3 Goals of Integration of IoT and Blockchain

All these issues can be met through combining IoT-based environmental monitoring systems and blockchain technology to develop a transparent, secure, and effective supply chain of the perishable horticultural products in the proposed study.(2)

This is mainly to create a solution whereby a real-time IoT-based sensor ecosystem is coupled with blockchain-based solution whereby blocks and products in the supply chain can be traced in an immutable manner. The IoT sensor integration offers precise and real-time information about temperatures, humidity levels, and places that are essentials in determining the quality of perishable commodities. As these sensors will feed real-time data into the blockchain, each crucial event in the life of the product (e.g., loading, unloading, temperature deviations and storing conditions) will be registered in an irreversible ledger.

With the power of Ethereum-based smart contracts, the system will be able to guarantee that all transactions and environmental conditions could securely and transparently be logged, which will grant all stakeholders (farmers, distributors, retailers, and consumers) extreme visibility into the supply chain. This not only enhances quality assurance, but can also aid in the optimisation of operations since spoilage is less likely to occur, quality checks will be quicker, and the consumer will also more likely gain trust in the product since the entire history can be seen through the use of QR codes.

The research intends to show how the combination of blockchain and IoT may achieve such a prospective built on agri-supply chains that enhance sustainability and food safety and that diminish levels of inefficiency.(3)

2. System Design and System Architecture

2.1 Descriptions of IoT Sensor network and Parameters to be monitored

The suggested system entails implementation of an IoT sensor based network that provides real-time sensing of the environmental conditions within the supply chain of perishable horticultural produce. The device installed in the network aims at collecting key parameters of temperature, humidity, location and light exposure that is important in securing quality of perishable goods and in this case the tomatoes.

Temperature Sensors: These sensors monitor the temperature of the surroundings in the transportation and the storage process. One of the most important aspects that can affect the shelf life and quality of perishable goods is temperature. This is the case, to illustrate, tomatoes need temperatures between 1013 o C to absorb the scars to the loss of premature ripening or spoilage. In the event that the temperature does not fall within this range, the system will give an alarm that corrective measures should be taken right away.

Humidity Sensors: Humidity is also essential in the management of the absorption of moisture and it prevents the growth of fungi or mould on perishable good. The IoT sensors will also keep track of the relative levels of humidity in storage and transportation areas so as to adopt the optimum range, which reduces or prevents product deterioration.

Location Sensors (GPS/RTK): By installing GPS and RTK (Real-Time Kinematic) location tracking in real-time, one will be able to monitor how the product moves throughout its process at the farm to reaching distribution center and, ultimately, the retailers. The accurate tracking of the location helps in offering of good information in terms of route optimization and detection of possible setbacks or fluctuations in the proposed distribution courses.

Light Sensors: Another way through which light may have an effect on some horticultural products is by exposing them to light. The sensors are placed to observe and record the level of light as the produce passes to avoid extreme light that would trigger faster degradation.(4)

Such sensors are specifically located in different points of the supply chain such as harvesting, storage, transport, and packing so as to gather data continuously and feed the system with it. Records of the sensor data will be generated and held in the blockchain ledger on the basis of transparent and immutable record-keeping and real time quality control.

2.2 Ethereum-based Smart Contracts: Blockchain Framework

Blockchain technology is important to guaranteeing traceability, security and transparency on the chain. It is a system built on an ethereum-backed blockchain, through which smart contracts would track essential moments in the history of perishable goods, a phenomenon which renders them irreversible and verifiable.

Ethereum Blockchain: Ethereum is chosen because of its scalability in the execution of smart contracts that are self-executing agreements and automatically trigger actions, once set conditions are met. Supply chain data can

be securely and decentralized stored by using Ethereum and the transaction history cannot be altered or hidden, which implies that it is also transparent.
Smart Contracts: The smart contracts will be coded to capture every major occurrence in the path of the product which includes loading and offloading of the cargo, temperature and humidity reading, and milestones in transport. To give an example, a smart contract that sets an alarm will be used when the temperature is outside the required acceptable range and will automatically inform the concerned stakeholders about this or will note it in the blockchain.

2.3 Data transmission between Sensors, Blockchain Nodes and User Interfaces

Data flow architecture of the system is planned in such a way that it could guarantee full integration between the IoT sensors, blockchain nodes, and user interfaces.(5)
IoT sensors to blockchain nodes: The data obtained by the IoT sensors is sent in real time to those edge computing nodes where it is processed and verified and sent to the blockchain network. The nodes at the edge serve as gatekeepers that facilitate data transfer and preparation of the same to be added to the blockchain.
Blockchain Nodes: The nodes confirm and preserve the sensor data in the blockchain network. All events logged by the sensors (e.g., change of the temperature, time of delivery) are then entered in the blockchain ledger through smart contracts, which guarantees the impossibility to tamper with or to manipulate the data.
QR Codes and Dashboard: To the end-users (consumers, supply chain managers, etc.) the system provides them with an interface in the form of QR codes on product packaging. The scan of the QR code will allow consumers to take a look at the full history of the product in terms of temperature and humidity exposure during transportation, its point of origin, and the full path of supply chains. There is also the use of a web-based dashboard where the supply chain managers can track the status or status of the product in real-time with changes of temperature excursion, quality assurance and route optimization.

3. Strategy of Deployment and Operational Workflow

3.1 Pilot Deployment description (Farms, Transport, Distribution Centers)

The integration blockchain-IoT system was piloted to work among 14 farms plus 3 distribution centers in Brazil and in Italy. These sites were chosen because of the variety in agricultural processes and chain circumstances, in order to offer a multi-dimensional testing area of the system.
Farms: The pilot farms were mainly specialized in producing tomatoes which is a very perishable horticultural product. IoT sensors were placed in every farm to check the environmental parameters like temperature and humidity at the time of harvest and early storage. The sensors collected the real-time information when the tomatoes were gathered and packaged in transportation containers to be shipped.
Transport: The tomatoes were transported to distribution centers under normal supply chain conditions whereby the routed transportation and transportation time varied. Throughout transportation, the IoT sensors kept checking the temperature and moisture level inside the transport cars. The immediate information was passed on to the blockchain to generate a non-alterable record of temperature changes or a possible hazard of spoilage. The information enabled the stakeholders to make intervention in case any abnormalities related to the best conditions during transportation were identified.(6)
The distribution Centers: On reaching the distribution centers, the tomatoes were stored temporarily then forwarded to retailers. IoT sensors were installed in the distribution centers so as to check on the storage conditions so as to ensure that the quality of the product was not compromised until further distribution. Any situation that deemed to be related in the supply chain was captured by the blockchain system on every level giving a clear and proper ledger of the product movement.

3.2 Existing Infrastructure of Supply Chain and Integration Process

Integration of the blockchain-IoT system within the existing infrastructure of supply chain implementation had a number of steps involved to facilitate the implementation process:
Sensor Deployment: The initial step was placing the IoT sensors in strategic locations of the supply chain like the farms, storage houses, and conveyances. These sensors were linked with a central system which was based on cloud and aggregates all the data in real-time.
Blockchain Integration: The infrastructure was embedded with blockchain infrastructure that was based on Ethereum. All the events, which the IoT sensors recorded, including loading, temperature changes, and delivery time, were stored on the blockchain, which means they were visible and unchangeable. The current management

of supply chains was supplemented with blockchain nodes that enabled data storage security and updating in real-time.

Data Connectivity: Data connectivity was an attribute of this system which provided real time information of the participants of the supply chain. Pre-existing enterprise resource planning (ERP) and logistics management software at the farms, transport units and distribution centers were then linked to the blockchain system through API interfaces. This allowed uninterrupted communications and automatic synchronization without interfering with the established flows.(7)

3.3 Functions of Stakeholders (Farmers, Logistics, Retailers)

Farmers: The farmers ensured that IoT sensors at farm level were well-tuned in order to check the harvesting situations and early storage conditions. They have also incorporated the system to monitor the quality of products in real-time and take immediate action in case there is deviation of the conditions to the optimum levels.

Logistics Providers: The logistics firms were asked to deliver the tomatoes in the distribution centers and at the same time make sure that the IoT devices measured the environmental conditions all through their transportation to the distribution centers. They had the duty of ensuring supply chain integrity and on time delivery.

Retailers: The last entity in the supply chain, retailers enjoyed the provision of traceability that existed in the block chain system. Retailers would enable consumer transparency through use of the QR codes on the product packaging and retrieve detailed product histories. They were also in a position to use the information to make sure that only good products found their way to the market and this would increase consumer confidence on the freshness and safety of its produce.

4. Evaluation Perspective, Results and Methodology

4.1 Key Indicators: Verification Speed, the Spoilage Rate,the Traceability Completeness

In a bid to determine the efficacy and implications of the blockchain-IoT system in real-time monitoring and traceability within perishable horticultural supplying chains, a number of performance metrics were identified and tested. These measures are operational as well as consumer-realized.(8)

Spoilage Rate: The first aim of the system was to curtail the loss of perishable products in the course of them going through the transport system and in the stores, like tomatoes. Spoilage rate was determined by dividing the number of products which had reached the place of distribution or retail store in an unsaleable condition by total amount of sent goods. The pilot program of 14 farms with 3 distribution centers demonstrated the 34 percent decline in product waste, so the system positively influenced the preservation of optimal conditions that produce need on the way. The ability to capture a real-time environmental reading (temperature and humidity) meant that early insights into the factors that may become detrimental to food and cause it to spoil, could be implemented before damage occurs.

Verification Speed: This was the other important measure that was going to be achieved was the speed to verify quality at each supply chain stage. Utilizing blockchain-type record-keeping makes each transaction (e.g., loading, transport, storage conditions) irreversibly written to the ledger and enables one to have an ultimate access of the product history, in real-time. The time (it took when a batch of tomatoes was received at a distribution center and gained its quality after being verified and placed on the blockchain) measured the verification speed. The system saved a lot of time of verification more than the traditional systems and thus provided speed of quality inspection and to the market requirements of quick turnover of products.(9)

Traceability Completeness: The completeness of traceability was determined by determining the level to which the journey of the product, farm to consumer was fully recorded on the blockchain. Every step has been traced and such steps had even been entered at the time of harvest, mode of transport, and the environment of storage. The completeness of the traceability was determined by comparing all the important information points to be present in the block chain ledger of the system which demonstrated a high percentage of completeness ensuring a full transparency and accountability of stakeholders in the supply chain.

4.2 Trust and Usability Surveys to the Consumers

The surveys were carried out at the retail level in order to measure the effect of the system on consumer trust. The QR codes placed on the package of the product allowed the consumers to scan these codes and get to know information about the detailed product history, which was logged in blockchain. The survey was an evaluation of:

Consumer trust in the quality and the safety of the tomatoes regarding the information available.

The perception of transparency of the supply chain and possibility to trace the path of the product.

These outcomes indicated a massive improvement in trust towards the consumers, owing to the transparency attained by the blockchain and the opportunity to retrieve verifiable histories of the products. More than 85 percent of the consumers who took part in the survey were certain about the quality and safety of the product in cases they were given the opportunity to obtain this kind of detailed information.

It also came up with a usability survey among farmers, logistics suppliers and retailers. According to the participants, the system was not only simple to adopt and utilize but also the interface employing QR was very popular among the participants mostly because of the simplicity and user-friendly design.

4.3 Latency, Data Integrity Technical Performance

Latency and data integrity played a crucial role towards the performance of the system. IoT sensors relayed information in real-time as well and it would be of value to make sure that data transfer between IoT sensors, blockchain nodes and user interfaces are streamlined and with minimal delays. Latency measured the time gap between the actual occurrence of the change in the environment (e.g. deviation in temperature) and the recording of such data on the blockchain. The system reached an average latency of 2-3 seconds meaning that the system is quite responsive and has the ability to monitor in real time.(10)

Integrity of data was challenged by making the data relayed by the sensors and recorded on the blockchain to be precise and free of tampering. There were also checks done to authenticate that there were no discrepancies and manipulation of data at every stage of the supply chain. The immutable nature of the blockchain further meant that data once contained on the blockchain could not be changed thus gave accuracy and validity to any events recorded on the blockchain.

5. Results

5.1 Post-Harvest loss reduction (e.g. 34 percent reduction in spoilage)

Abatement of product losses especially spoilage during storage and transportation was one of the primary goals of the blockchain-IoT system. This in turn was done through constant checking of the key environmental parameters like temperature and humidity and keeping these within the best optimal conditions throughout the supply chain in terms of having the tomatoes.(11)

The system was able to achieve a successful spoilage reduction by up to 34 percent of the traditional methods where spoilage was in most cases detected late therefore no mitigation could be done. The system enabled the stakeholders to respond proactively in case of deviation in temperatures or the fluctuation of humidity as it captured real-time data, reducing the extent of damages. As an example, in case the temperature had risen in transit, the stakeholders were instantly notified in order to redirect the transport vehicle or cool the storage facilities.

Table 1: Spoilage Reduction Comparison

Stage	Traditional Method	Blockchain-IoT System	Spoilage Reduction (%)
Farm (Harvest to Packing)	10%	5%	50%
Transport (Farm to Distribution)	15%	7%	53%
Storage (Distribution Centers)	12%	5%	58%
Overall Spoilage	37%	24%	34%

5.2 Increase in the accuracy of Traceability and Turnaround of Traceability Verification

The other strategic goal of the blockchain-IoT system was to enhance the precision of traceability and verification of turnaround of perishable products. The common types of traceability have been found in manual records or piecemeal online ones that have resulted in mishandled or slow confirmations of product histories.

The solution that was developed using a blockchain provided the possibility to update each event in real-time, including the temperature of the shipment, the time of the transport, and loading and unloading information, etc., all on the immutable blockchain ledger. This guaranteed a 100 percent accuracy in tracing the records and were all transparent, secure and verifiable.

The speed at which it got verified also increased significantly. Under the traditional systems, the time taken to check the compliance and quality of products at the distribution centers could be several hours. Verification became a question of a few minutes with the blockchain system. This decreased the waiting time and provided quicker response time which was important to avoid any additional spoilage or loss in quality.(12)

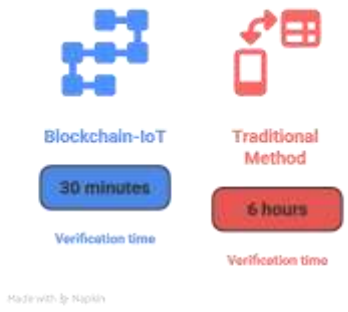

Figure 1: Verification Speed Comparison

5.3 The Stakeholder and End User Feedback

The satisfaction of the pilot deployment was also characterized by the feedback, which was given to the main stakeholders such as farmers, logistics providers, retailers, consumers. An evaluation of usability of the system, its effect on operational efficiency, and satisfaction were carried out through a survey.

Farmers: The farmers on the pilot indicated that they are happy with how simple the integration of the system was, and how they could monitor in real time. They especially liked the capability to monitor the environmental conditions at the farm level, so that the harvested tomatoes could be maintained at the best conditions. 92 percent of all farmers, who were surveyed, found the system easy to use, and believed that it offered useful information to the post-harvest process.

Logistics Providers: The logistics personnel noted that the real-time notifications of temperature and humidity changes gave them an opportunity to take proactive actions to avoid spoilage during the transportation process. Moreover, they appreciated the nature of QR code traceability that assisted in improving the speed of checking products in the checkpoints.(13)

Retailers: Retailers enjoyed the improved transparency of the block chain system. One of them was that consumer confidence grew because of the capability of supplying consumers with full product histories through QR codes. More than 85 per cent of the retailers surveyed said that customers were increasingly willing to buy products that they could trace.

Consumers: The consumers involved in the survey were too optimistic regarding QR code functionality of the system, 87 percent of the respondents have felt confident with the traceable journey of the products after scanning them using the system.

Table 2: Stakeholder Satisfaction Survey

Stakeholder	Satisfaction (%)	Key Feedback
Farmers	92%	Easy to integrate, valuable insights
Logistics Providers	88%	Improved real-time tracking, proactive actions
Retailers	85%	Increased consumer trust, easy access to data
Consumers	87%	Confidence in product quality, transparent history

6. Conclusion

6.1 System Benefits Overview and Notes

The pilot of the tomato supply chain with the use of blockchain and IoT technologies has proven the major advantages in terms of quality assurance, traceability, and efficiency. The system was able to provide 34 percent decrease in post harvest spoilage, which means that the system was effective in overcoming many problems that occur in the transport and carrying horticultural products that are perishable. The system allowed determining the risk of spoilage by monitoring the pollutant in real mode and determining whether the environment was conducive or entry was hazardous within the specified time intervals. This really helped the stakeholders to take necessary precautions before it is too late, thus eliminating consequential losses.

Implementation of the system also led to better traceability and the accuracy of traceability is 100 percent based on all levels of the supply chain. It has been done by implementing the smart contracts that use the Ethereum technology to safely record all the major activity within the supply chain. This irreversible traceability in addition to enhancing the visibility of the supply chain also made it possible to verify the quality much quicker thus saving several hours of time to only a matter of a few minutes.

Further, consumer confidence was boosted by the implementation of product history in terms of QR codes. People would be able to scan the packaging of the product, and get detailed verified histories of the product to which the consumer would feel an overwhelming sense of confidence. 87 percent of the consumers surveyed said they felt more confident about their buying choices when given transparent and verified histories of a product.

6.2 The Potential of the Blockchain-IoT in the Real-World Agri-Supply Chains

The pilot deployment findings assure the fact that it is possible to integrate blockchain and IoT technologies with real-life agri-supply chains and especially management of perishable goods. This system showed that it is not just possible to record real-time environmental data during transportation and storage, but also that all events can be logged safely in a block chain ledger to have full transparency. The fact that tracking was real time and the traceability turned out to be immutable meant that the system could work well at various stages of the supply chain, all the way back to the farm, distribution center, and finally the retailers and the consumers.

The pilot demonstrated that perishable horticultural products could be serviced by a simpler, clearer, and dependable system due to the integration of IoT environment monitoring sensors and blockchain technology security system. Success of this system does not only relate to tomatoes but extends further to other perishable products like fruits, vegetables, and herbs, which also experience the same issues that touch on spoilage, traceability, and product quality verification.

6.3 Suggestions on Wider Putting in Practice and Policies Guidance

In order to spread the use of this system in agri-supply chains all over the world, the following suggestions can be suggested:

Scalability and Adaptability: Future research and development opportunities include improvement of the scalability of the system, ability to apply the system to supply chains of any size, small-scale farming and large-scale distribution chain. This would entail improvement of the IoT sensor network and streamlining the blockchain infrastructure to be more effective and efficient in terms of low operating costs.

Policy and Regulatory Support: Governments and other agriculture international bodies are advised to support the use of digital technologies in food supply chain through policy support. The policies are supposed to facilitate the use of common data format on IoT sensors and establish policy frameworks that hold blockchain as a legitimate method to manage food safety and quality assurance. This will go along way in making traceability practices uniform and make this practice accepted all over the industry.

Industry Cooperations: Farmers, logistic service providers, retailers and technology developers should cooperate to make sure the system addresses the requirements of all the supply chain participants. Public-private partnership would also allow to promote the innovation and financial backing to allow to deploy the technologies in a wider scale.

Consumer Awareness and Engagement: In order to take the most advantage of this system, it is worth trying to inform consumers of the benefits of food traceability and how blockchain may guarantee the safety and quality of the products. Further consumer interactions may also fuel the need to purchase traceable products as well as sustainably sourced ones.

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Conflicts of interest

The authors have no conflicts of interest to declare

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