Enhanced Food Quality by Digital Traceability in Food Processing Industry

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ABSTRACT

This study explores the enhancement of quality traceability in the food processing industry through the integration of modern digital tools, specifically blockchain technology. By combining a thorough literature review with the analysis of real-case studies, the research investigates current digital trends and their practical applications in the food processing sector. The findings show that blockchain-based approaches significantly improve supply chain transparency and quality management. Despite the potential benefits, the study also identifies challenges in practical implementations, such as resistance to adoption and the need for substantial investment in digital infrastructure. The research highlights the limited cultural attitude within the industry towards the comprehensive adoption of these modern tools, with their usage mostly confined to isolated case studies rather than a structured, widespread experimental orientation. Practical implications include providing businesses with guidelines for implementing digital tools to enhance quality traceability and management. Social implications underscore the critical role of these tools in meeting societal demands for food safety and transparency, particularly regarding information on raw materials, processing, and preservation methods. Thus, this paper offers a comprehensive overview of the use of blockchain and other digital tools to improve quality traceability in the food processing industry, contributing valuable insights and guidelines for future implementations.

Keywords: Quality 4.0, Food Processing Industry, Traceability, Blockchain.

INTRODUCTION AND BACKGROUND

In the current landscape of the global food industry, the emphasis on traceability stands out as a crucial component for ensuring food safety and quality. This focus has been spurred by various food scandals, highlighting the need for transparency across the supply chain. For instance, the 2008 melamine contamination in China, which resulted in severe health issues for infants, exposed significant gaps in supply chain transparency and quality control [1]. Similarly, the 2013 horsemeat scandal in Europe revealed widespread mislabeling of food products, leading to a loss of consumer trust and substantial financial repercussions for the involved companies. Additionally, the 2015 E. coli outbreak at Chipotle restaurants in the USA, which sickened dozens of customers, underscored the deficiencies in supply chain monitoring. Another significant incident was the 2017 Fipronil egg contamination in Europe, which necessitated the recall of millions of eggs due to harmful insecticide contamination [2]. These incidents have collectively driven the food industry to seek more reliable and transparent solutions in the supply chain.

Traceability, defined as the ability to track an entity's history, application, or location through recorded identifications, serves both to meet consumer demands for food safety and transparency and as a vital mechanism for businesses to boost competitiveness and optimize production processes. It ensures product traceability "from farm to fork", documenting each product lifecycle stage to facilitate "chain traceability" [3].

In the European market, traceability is categorized into mandatory and voluntary type, each serving distinct purposes and providing different levels of product quality information. Mandatory traceability, aimed primarily at financial transactions, often lacks in-depth product quality details. In contrast, voluntary traceability allows supply chain participants the flexibility to choose which data to collect, facilitating a more detailed and qualitative traceability system when additional information is voluntarily included [4].

Following food safety incidents, the European Union (EU) has reinforced traceability as a legal requirement to enhance food safety and hygiene. Regulation (EC) No 178/2002 by the European Parliament and of the Council established core principles and necessary procedures for food law, including the creation of the European Food Safety Authority (EFSA). This regulation enables consumers to trace the journey of food, feed, animals intended for food production, or substances across all production, processing, and distribution stages [5]. Additionally, the adoption of technological innovations, particularly the Internet of Things (IoT), Radio Frequency Identification (RFID), and blockchain technologies, has significantly advanced traceability systems within the food processing industry. These technologies enhance the efficiency, accuracy, and reliability of data management throughout the food supply chain [6].

The IoT, specifically, has revolutionized data collection in the agri-food sector by utilizing devices and wireless sensors for continuous monitoring of product quality, environmental conditions, and logistics. This technology enables real-time data collection and transmission, which improves the overall traceability and management of the supply chain [7, 8].

RFID technology, an advancement over traditional barcode systems, uses electromagnetic fields to automatically identify and track tags attached to objects. RFID systems consist of tags, readers, and a data management system. Each tag has a unique identifier, which enhances the traceability of items throughout the supply chain by providing detailed insights into the product's journey without requiring direct visual contact [9, 10].

Additionally, the sector has adopted technologies like Wireless Sensor Network (WSN), Near Field Communication (NFC), Datamatrix, and QR Codes to further improve traceability. WSNs gather and relay environmental data, providing real-time monitoring of conditions such as temperature and humidity throughout the supply chain, crucial for maintaining the quality and safety of perishable goods [11]. NFC facilitates short-range device communication, enabling easy access to traceability information with a simple tap of a smartphone, which enhances transparency and allows consumers to make informed choices [12]. Datamatrix, a type of two-dimensional barcode, efficiently stores a large amount of data in a small space, including text, numeric, and binary information, making it particularly useful for tracking products throughout the supply chain [13]. QR Codes, similar to Datamatrix, can store extensive information and are easily scanned by smartphones and other devices, providing consumers and supply chain stakeholders with access to comprehensive product data [14].

While IoT-based traceability systems have significantly improved the monitoring and assurance of food quality, their reliance on centralized server-client models, predominantly managed by third-party cloud infrastructures, introduces several vulnerabilities. This centralization forces all stakeholders, including consumers, to depend on a singular entity for the storage, transmission, and sharing of traceability information, creating a potential bottleneck and single point of failure in the traceability process [15]. Such a system structure raises critical concerns about data integrity and security, including risks associated with information loss, data tampering, false statements, and the adulteration of food products. It implicitly suggests that the entire agri-food supply chain (AFSC) is underpinned by a framework of trust, requiring each participant to accurately and honestly input data into the system.

Moreover, the AFSC faces myriad challenges that demand comprehensive attention and action. These include the potential for loss or theft of products, the adulteration of goods, the sale of expired or counterfeit items, non-compliant labeling practices, and the increasingly vocal consumer demand for transparency, verifiability, and safety in the food supply chain. The supply chain's complexity is further amplified by the involvement of a wide array of actors, spanning internal entities responsible for production, processing, logistics, and sales, to external entities like consumers and regulatory bodies. The traditional approach to managing traceability data has often been centralized, managed by a select few authorized agencies or businesses, which poses inherent risks of data manipulation by individual entities controlling traceability data for their segments of the supply chain. Efficiently addressing the myriad challenges within the AFSC is crucial for enhancing the reliability and integrity of informational exchanges, a key factor for the sector's long-term success and sustainability. In this context, a robust traceability system is essential, serving not just to improve operational efficiency and quality but also to provide vital information that can lead to cost reductions, improved yields, better product quality, minimized waste, and increased employee productivity.

Developing a universal traceability system that meets the diverse needs of various food supply chains faces challenges due to standardization issues. Supply chain actors often create proprietary solutions, leading to compatibility problems, reduced effectiveness, and higher costs. Progress has been made with the adoption of EAN/UCC (GS1) standards by the Uniform Commercial Code Council (UCC) and the International Article Numbering Association (EAN), requiring records of logistical unit serial numbers (SSCC), identification numbers (GTIN), and location numbers (GLN), aiming for global harmonization [6].

Despite these advancements, the need for a flexible, scalable traceability framework persists. Blockchain technology, offering a decentralized and secure ledger, emerges as a solution to enhance supply chain transparency, mitigate trust issues, and improve data integrity, supporting a comprehensive history of food products from origin to distribution [15].

Quality 4.0, which integrates advanced digital technologies into quality management systems, plays a crucial role in modernizing traceability processes. By leveraging digital tools such as blockchain, IoT, and Artificial Intelligence (AI), Quality 4.0 enhances data accuracy, operational efficiency, and decision-making capabilities, ultimately leading to improved product quality and consumer trust. Quality 4.0 represents the convergence of digital transformation with quality management, emphasizing the use of real-time data, analytics, and interconnected systems to improve quality outcomes [16–18]. This approach facilitates proactive quality management, predictive maintenance, and enhanced compliance with regulatory standards, all of which are critical in the highly regulated and quality-sensitive food industry. Food Quality 4.0 is an emerging concept that refers to the use of advanced digital tools in food analysis to obtain quick and reliable assessment of food quality [19, 20]. Similarly, Food Safety 4.0 evolves traditional food safety practices by adopting a proactive approach that uses advanced digital technologies to prevent and quickly address potential food safety risks [21].

The combination of blockchain with IoT devices and digital tools is set to transform supply chain management by enabling end-to-end tracking of food products. Recent pilot projects by businesses indicate a trend towards developing more efficient and flexible traceability systems. Moreover, a successful blockchain application in the food sector requires collaboration between multidisciplinary experts, including agri-food specialists and IT professionals, to address supply chain complexities effectively. This collaborative approach is essential for creating secure, universally applicable blockchain-based traceability systems [22].

In this context, the purpose of this paper is to examine the enhancement of quality traceability in the food processing industry through the integration of modern digital tools, such as blockchain technology. The study combines a thorough literature review with the analysis of real-case studies to explore the practical application of these technologies and their potential to improve supply chain transparency and quality management.

Focusing on the transformation and distribution phase of the food value chain, the present paper aims to highlight digitalization's impact on supply chain transparency and quality management. The study evaluates digital trends and their practical applications, offering insights into how these tools can meet societal demands for food safety, quality, and transparency. It provides valuable insights and guidelines for the industry, underlining the need for transparency in handling information about raw materials, processing, and preservation.

The paper highlights a crucial shift from traditional centralized data management systems towards a more decentralized, secure, and transparent approach facilitated by blockchain technology. This change aims to overcome challenges in current traceability systems like data integrity and stakeholder trust. By incorporating empirical case studies, this research contributes to the advancement of discussions on food supply chain management. It aims to pave the way for enhanced quality assurance and transparency in the industry, meeting the varied needs of different food supply chains.

The rest of the section provides an overview of the agri-food industry and the role of blockchain technology, and other alternatives, in traceability.

The Agri-Food Industry

In the late 1960s, Louis Malassis defined a supply chain as the path followed by a product within the agri-food apparatus. It concerns all the agents or actors (enterprises and administrations) and operations (production, distribution, financing) that contribute to the formation or transfer of the product up to its final stage of use, as well as the mechanisms for adjusting the flows of factors and products along the supply chain and in its final phase [23] .

The Food Value Chain (FVC) is a key concept in the food sector that represents the complete process through which food is produced, processed, distributed, and ultimately made available to consumers. This chain involves a series of actors and activities working together to bring food from the agricultural production phase to consumers' tables. The FVC is notoriously characterized by significant complexity and fragmentation. Some of the features that make it different and certainly more complex than others are summarized in the following points [24]:

1. Short life cycle: most food products have a very short life cycle, necessitating rapid processing and reduced storage times.
2. Perishable goods: perishable goods require specific transport and storage conditions to ensure freshness and quality.
3. Agile production cycles: production operations must often adapt to frequent setup cycles due to product seasonality.
4. Product diversification: there is considerable differentiation between products within the chain, with many varieties and options available.
5. Rigorous quality controls: given the importance of food safety, strict quality controls and adherence to various national and international regulations and directives are necessary.

Given its peculiarities, FVC management requires active cooperation and maximum coordination among the diverse range of interested actors, with the common goal of generating benefits for each participant in the system and fully satisfying consumer needs. The key actors of the FVC are analyzed as follows:

1. Agricultural producers: these are the growers, ranchers, and fishermen who produce food raw materials such as fruits, vegetables, meat, fish, and dairy.
2. Agricultural input suppliers: these include companies that supply fertilizers, pesticides, farming equipment, seeds, and other resources needed for agricultural production.

3. Processors: these actors transform raw materials into packaged food products ready for sale. Processing operations are of two types: primary and secondary. Primary processing involves transforming inedible raw materials into food ingredients, including activities like cleaning, peeling, grading, and packaging. The ingredients obtained from primary processing may be destined for retail sale or for food factories to be used as components in secondary processing. The latter includes activities aimed at transforming these ingredients into foods ready for consumption, varying from grinding grain to obtain flour to pressing juice from fruit, producing cheese from milk to preparing ground meat.
4. Distributors and wholesalers: these intermediaries purchase large quantities of food products from producers and distribute them to retail stores, restaurants, and other destinations.
5. Restaurants and retailers: these are the places where end consumers purchase food, including restaurants, supermarkets, markets, and specialty stores.
6. Transporters and logistics: these operators handle the transportation of food products along the value chain, ensuring that products reach retail points safely and promptly.
7. Food safety and regulatory authorities: government agencies and regulatory organizations play a significant role in ensuring food is safe for consumption and complies with health regulations.
8. Consumers: end consumers are a critical element of the food value chain, as their choices influence food product demand and purchasing behaviors.
9. Non-Governmental Organizations (NGOs): some NGOs address issues related to sustainable agriculture, food security, and combating food waste.
10. Financial service providers: financial institutions offer lending and investment services to support food production and distribution activities.

In the paper, the focus will be exclusively on the second phase of the food value chain. This phase begins after the raw materials have been acquired by processing companies and encompasses the entire process of transformation and distribution.

Blockchain Technology in the Agri-Food Supply Chain

The launch of blockchain technology in 2008 by Satoshi Nakamoto, a pseudonym, introduced a groundbreaking approach to digital transactions with the creation of Bitcoin. This technology enabled direct online payments between parties without a financial intermediary, challenging traditional transactional paradigms [25]. Blockchain's decentralized digital ledger records transactions in a series of cryptographically linked blocks, ensuring security and transparency. This architecture facilitates a distributed consensus, allowing participants to agree on the ledger's state without central oversight, revolutionizing trust in digital exchanges by eliminating the need for traditional intermediaries.

A key feature of blockchain is its immutability; once information has been validated and recorded, it cannot be erased. Each block in the blockchain comprises four fields: the block number, stored data, a value representing the hash of the preceding block, and a value representing its own hash. This cryptographic linking of blocks ensures data integrity and prevents tampering. The blockchain's immutability is bolstered by peer-to-peer (P2P) distributed networks, which store and transfer data among nodes without a central storage point, enhancing data security.

To elucidate the practical mechanics of a blockchain transaction, consider the example of "Alice buying a pizza from Bob" using Bitcoin. This transaction involves several steps, from creating and digitally signing the transaction to its validation through mining and eventual inclusion in the blockchain, thereby recording the transfer of Bitcoin ownership from Alice to Bob [26].

Since its creation, blockchain has undergone rapid evolutionary processes. Initially conceived as the technology underpinning the pioneering cryptocurrency Bitcoin, it has demonstrated broader potential. Over the years, various blockchain variants have emerged, each with specific features. These developments are often segmented into three phases:

- Blockchain 1.0: focuses on cryptocurrencies and distributed ledgers for financial transactions.
- Blockchain 2.0: offers greater complexity and flexibility, extending beyond cryptocurrency transactions to include smart contracts that automate agreements between parties. Ethereum is widely regarded as a significant example of Blockchain 2.0.
- Blockchain 3.0: aims at optimizing performance to handle more transactions and data efficiently, focusing on interoperability among different blockchain networks, scalability, and expanding sector-specific applications, such as supply chains in the agri-food sector.

Blockchain technology encompasses several critical elements, including a secure ledger, consensus mechanisms, and specific architectural frameworks, supported by various open-source solutions.

A secure ledger in blockchain ensures that all transactions are recorded in a tamper-proof manner. This is achieved through cryptographic hashing and the chaining of blocks. Each block contains a cryptographic hash of the previous block, a timestamp, and transaction data, making it practically impossible to alter any information without changing all subsequent blocks. This immutability is critical for maintaining the integrity and trustworthiness of the data [25].

Consensus mechanisms are protocols that ensure all nodes in the network agree on the state of the blockchain. Various consensus algorithms exist, each with its strengths and weaknesses:

- Proof of Work (PoW): used by Bitcoin, PoW requires miners to solve complex mathematical problems to validate transactions and add new blocks. This process is secure but energy intensive.
- Proof of Stake (PoS): used by Ethereum 2.0 and Cardano, PoS selects validators based on the number of coins they hold and are willing to "stake" as collateral. PoS is more energy-efficient than PoW [27].
- Byzantine Fault Tolerance (BFT): used by Hyperledger Fabric, BFT algorithms ensure consensus even if some nodes act maliciously. This is achieved through multiple rounds of voting among nodes [28].

Blockchain architecture refers to the structural design of a blockchain system, including its protocols, network design, and consensus mechanisms. There are different architectural models based on the needs of the application:

- Public blockchains: open to anyone and maintained by a distributed network of nodes. Examples include Bitcoin and Ethereum.
- Private blockchains: restricted to a specific organization or group, offering controlled access and faster transaction processing. Examples include Hyperledger and Corda.
- Consortium blockchains: governed by a group of organizations, providing a balance between decentralization and control. Examples include Quorum and Ripple [29].
- Hybrid blockchains: combining features of both public and private blockchains, hybrid blockchains allow for managed access and privacy while maintaining some decentralization. Examples include Dragonchain [30] and IBM Food Trust [31].

Choosing the right blockchain type depends on the need for decentralization, control, privacy, and open access. Kramer et al. [32] emphasized that selecting a specific blockchain platform is crucial for the economic success of a project and for optimizing supply chain management in agri-food networks engaged in vertical cooperation. This selection process is vital for achieving the desired outcomes in transparency, efficiency, and trust within the supply chain.

Several open-source solutions facilitate the implementation of blockchain technology. Hyperledger Fabric is a modular and extensible blockchain framework designed for enterprise use, supporting pluggable consensus protocols and known for its scalability and flexibility [33]. Ethereum is a decentralized platform that runs smart contracts on a custom-built blockchain, with its open-source nature and robust developer community making it a popular choice for various applications [34]. Corda, designed specifically for business, is an open source blockchain platform that enables complex transactions and restricts data access to only those who need to know [35]. Quorum, an enterprise-focused version of Ethereum, offers enhanced privacy and performance, making it suitable for applications requiring high throughput and private transactions [36].

Smart contracts, conceptualized by Nick Szabo in the 1990s, are key in automating and enforcing contract terms directly through code when predefined conditions are met, with no need for intermediaries [37]. Residing on the blockchain, they are immutable and activated by specific triggers, documenting transactions in a shared ledger [38]. These contracts range from being deterministic, functioning independently on the blockchain, to non-deterministic, requiring external data via "Oracles" to execute actions based on real-world events [39].

The integration of blockchain and smart contracts significantly enhances traceability and efficiency in the agri-food supply chain. Blockchain's immutable ledger ensures every transaction is recorded and cannot be altered, which guarantees transparency and verifiability at each step of the supply chain. This traceability can be measured by tracking the percentage of supply chain events recorded on the blockchain compared to the total number of events [40].

Operational efficiency is improved by automating processes through smart contracts, reducing the need for manual interventions, and thereby decreasing the time and cost associated with administrative tasks. Efficiency can be measured by the time saved per transaction, reduction in administrative costs, and the speed of transaction processing. Blockchain's decentralized nature ensures that data is not stored in a single location, reducing the risk of data breaches. Data integrity can be measured by the number of data discrepancies detected before and after blockchain implementation [39].

Implementing blockchain in the agri-food supply chain requires robust IT infrastructure, including distributed ledger technology (DLT) platforms, secure servers, and network capabilities. Input data for blockchain includes information from various stages of the supply chain, such as production details, shipment tracking, quality control reports, and certification details. This data must be collected through sensors, IoT devices, and manual entries. Effective implementation also requires collaboration between IT specialists, supply chain managers, and domain experts to ensure the system meets all technical and operational requirements [27, 41].

The initial setup costs of blockchain include developing or purchasing blockchain platforms, integrating them with existing systems, and training staff. These costs encompass hardware, software, and labor. Ongoing maintenance involves continuous investment to maintain the blockchain infrastructure and ensure its security, along with updating systems and managing data storage. Additionally, interdisciplinary challenges arise, as implementing blockchain in the agri-food supply chain requires expertise from multiple fields, complicating coordination and increasing costs [28].

Efficiency in the agri-food supply chain can be defined by several metrics, which are outlined in the following. The speed of transactions is measured by the time taken to record and verify transactions on the blockchain. The reduction in fraud and errors is quantified by the decrease in fraudulent activities and data entry errors due to blockchain's transparency and immutability. Cost savings are evaluated by the reduction in operational and administrative costs from automated processes and improved data integrity. Regulatory compliance is measured by the ability to meet regulatory requirements efficiently through transparent and verifiable records [40].

Alternatives to Blockchain Technology

In addition to blockchain, there are several alternative technologies that can enhance traceability and transparency in the agri-food supply chain. Each of these alternatives offers unique advantages and disadvantages, making them suitable for different scenarios depending on the specific requirements of the industry.

Distributed databases, such as Apache Cassandra and Amazon DynamoDB, spread data across multiple nodes, ensuring redundancy and high availability. These systems can achieve high transaction throughput and scalability without relying on consensus mechanisms, which are fundamental to blockchain. This makes distributed databases particularly effective for real-time applications that require high-speed transactions. However, unlike blockchain, these databases are typically controlled by a single entity, which can pose risks related to data manipulation and central points of failure. Moreover, distributed databases do not provide an immutable ledger of transactions, which is a critical feature of blockchain for ensuring data integrity and traceability [42, 43].

Various consensus algorithms also provide alternatives to the traditional PoW used in many blockchains. For instance, PoS, used by platforms like Ethereum 2.0 and Cardano, is more energy-efficient than PoW and can provide faster transaction times. Nonetheless, PoS can lead to centralization if a small number of stakeholders hold a significant portion of the stake [27, 44]. BFT algorithms, such as Practical Byzantine Fault Tolerance (PBFT) used in Hyperledger Fabric, offer high throughput and low latency, making them suitable for enterprise applications, but they typically require a known set of validators, which can limit decentralization [28]. Proof of Authority (PoA), used by VeChain, relies on a small number of trusted nodes to validate transactions, offering high efficiency and security, but at the cost of reduced decentralization [45].

Hybrid approaches combine elements of blockchain with other technologies to leverage the strengths of multiple systems. For example, IBM Food Trust integrates blockchain with traditional databases to enhance traceability while maintaining high performance and scalability. Hybrid systems offer flexibility and can be tailored to meet specific needs, balancing decentralization, performance, and scalability. However, implementing such systems can be complex, requiring careful coordination between different technologies, and potentially leading to higher implementation and maintenance costs [46].

These alternatives each offer distinct benefits and trade-offs. Distributed databases provide high transaction throughput and redundancy but lack decentralization. Different consensus algorithms provide various efficiencies and security levels, with varying impacts on decentralization. Hybrid approaches leverage multiple technologies for enhanced functionality, but they can be challenging and costly to implement. Understanding these alternatives allows stakeholders to make informed decisions about the most suitable technology for their traceability and transparency needs in the agri-food supply chain.

Paper outline

The rest of the paper is structured as follows. In the "Methodology" section, a mixed-method approach, including literature review and business case study analysis, is presented. The "Literature Review" section reviews existing studies on blockchain and IoT applications in food traceability. The "Business Case Studies" section explores practical implementations of blockchain technology in the food processing industry. The "Challenges and advantages in the application of blockchain technology" section presents a detailed analysis of the principal challenges and advantages associated with the utilization of blockchain technologies and other digital tools to enhance traceability within the food production industry. This analysis is derived from the comprehensive review of existing literature and the detailed examination of case studies presented in the previous sections. In section "Guidelines for Designing a Traceability System for the Food Processing Industry," guidelines based on existing literature and best business practices are proposed to address the complexities of the food processing supply chain. Finally, the "Conclusions" section summarizes the study and suggests directions for future research.

METHODOLOGY

This study adopts a mixed-method approach to examine the enhancement of quality traceability in the food processing industry through the integration of modern digital tools such as blockchain technology. A mixed-method approach combines qualitative and quantitative research methods to provide a comprehensive analysis of a research problem [47]. The methodology consists of two primary components: a thorough literature review and a case study analysis.

The literature review (see Literature review section) aims to provide a comprehensive understanding of current digital trends and technologies employed in the food processing industry. This includes an exploration of the IoT, RFID, and blockchain technologies. The review synthesizes findings from a wide range of scientific articles, conference papers, book chapters, and reviews. It highlights the strengths, weaknesses, and gaps in existing research, thereby establishing a foundation for the case study analysis.

The case study analysis (see Business case studies section) involves an in-depth examination of real-world implementations of blockchain technology in the food processing industry. Several case studies are selected based on their relevance, diversity, and the depth of information available. The criteria for selecting these case studies include the scale of implementation, the specific digital tools used, and the documented outcomes in terms of traceability and quality management.

The selection criteria justification for the chosen case studies focuses on their diverse sectors, significant strides in blockchain implementation, and common need for transparency, trust, and brand enhancement. Placido Volpone S.r.l., Spinosa S.p.A., and Bofrost Italia were specifically selected to provide a comprehensive view of blockchain applications in different contexts.

Placido Volpone S.r.l. represents the initial phase of blockchain application, focusing on pure data notarization without an external certifying body. This case highlights both the potential and limitations of blockchain when solely relying on reputational risk for data integrity, making it crucial for understanding foundational applications in a controlled environment. Spinosa S.p.A. and Bofrost Italia illustrate the evolution towards more verifiable and transparent traceability solutions, involving multiple stakeholders and extending the supply chain to external suppliers. These examples provide insights into the intermediate complexity of blockchain integration.

Additional cases such as Carrefour Italia and Lavazza were selected for their unique challenges and extensive supply chains. Carrefour Italia's implementation in a large-scale retail environment and Lavazza's international supply chain offer perspectives on scalability and the integration of IoT and Agriculture 4.0 tools. Agriculture 4.0 refers to the adoption of advanced digital technologies in agricultural practices, including IoT, AI, robotics, and data analytics, aimed at increasing productivity, efficiency, and sustainability [48]. Completing the panorama, TATTOO WINE project by Blockchain Wine Ltd. represents an innovative blend of traceability and tokenization. This project establishes an online marketplace that connects businesses and consumers worldwide, demonstrating the expansive potential of blockchain technology in the food processing industry.

The selection criteria include the scale of implementation, specific digital tools used, and documented outcomes in terms of traceability and quality management. Expert testimony from an anonymous Tech Strategist at Microsoft, with previous experience as the Global Blockchain Traceability Product Strategy Lead and Innovation Manager at Ernst & Young (EY), provided critical insights and access to internal documents. This expert's involvement with several blockchain projects, including those of Placido Volpone, Bofrost, and Spinosa, was instrumental in our analysis.

The analysis followed a structured approach to ensure a thorough understanding and meaningful conclusions. The first step involved extensive data collection, where detailed information about each case study was gathered from multiple sources, including company reports, academic articles, industry publications, and interviews. This comprehensive data collection provided a solid foundation for understanding the context, implementation processes, and outcomes of each case.

Next, the collected data underwent systematic analysis to identify common patterns, challenges, and successes in the implementation of blockchain technology. The analysis focused on key metrics such as the degree of supply chain transparency achieved, improvements in quality management, and any efficiencies or cost reductions observed. This step traced the evolution of blockchain application, from simple data notarization to more sophisticated and verifiable traceability solutions involving multiple stakeholders.

Finally, the findings from the different case studies were compared and synthesized to draw broader conclusions about the efficacy of blockchain technology in enhancing traceability within the food processing industry. The insights gained from this comparison were used to propose a model for an effective traceability system, integrating the lessons learned from each case study.

The analysis of existing literature and case studies has enabled the definition of the principal challenges and advantages associated with the utilization of blockchain technologies and other digital tools to enhance traceability within the food production industry (see section “Challenges and advantages in the application of blockchain technology”). This comprehensive overview provides an understanding of the practical implications of these technological solutions and offers guidelines for their effective implementation.

Finally, guidelines based on existing literature and best business practices are proposed for designing a traceability system to address the complexities of the food processing supply chain (see section “Guidelines for designing a traceability system for the food processing industry”).

LITERATURE REVIEW

The development of this research involved a thorough literature review, drawing from a diverse array of sources including scientific articles, conference papers, book chapters, and reviews. Initial observations indicated that studies prior to 2012 were primarily focused on traceability within the AFSC exploring IoT technologies. However, from 2016 to the present, a significant shift has been noted towards blockchain technology as a potentially more promising development for establishing an efficient traceability system. Notably, no publications on blockchain applications before 2016 were found, suggesting that research on Blockchain Technology (BCT)-based traceability in the AFSC has emerged recently but it is growing exponentially. To substantiate this observation, an analysis on Scopus database was performed, utilizing the search string ("Agri-food" OR "food") AND "blockchain" AND "traceability", without imposing any publication year restrictions (see the results shown in Figure 1). This search resulted in a total of 725 documents up to the end of 2023, each analyzing the role of blockchain across various segments of food supply chains, including meat, fruits and vegetables, grains and cereals, oil, wine, and fish. The publication curve demonstrates a consistent annual increase, marked by a notable surge in recent years. The increase in documents to 725 by the end of 2023 underscores the burgeoning interest and research activity in the intersection of blockchain technology and AFSC traceability, reflecting the sector's dynamic evolution and the growing recognition of blockchain's potential to enhance traceability systems.

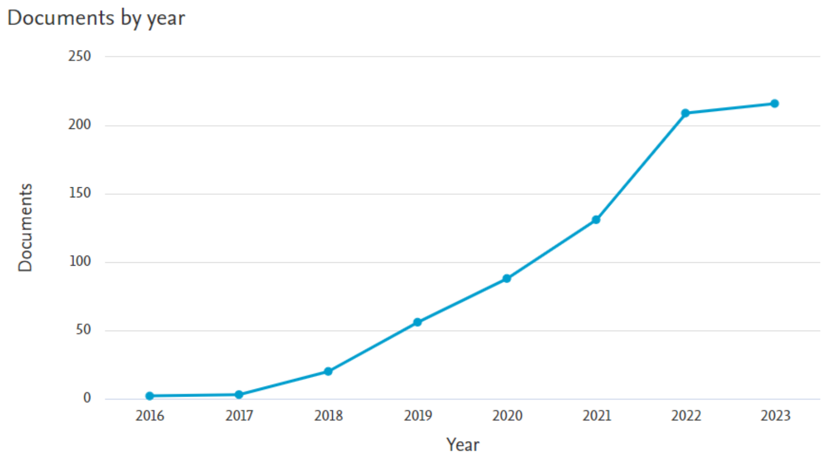

Figure 1 – Annual Count of Blockchain-Related Publications in Agri-Food Traceability (2016-2023). Source: Scopus.

Despite the overall growth trend, a noticeable slowdown in publications was observed in 2023. Several factors could contribute to this deceleration. One possible reason is market maturity; as blockchain technology matures, early adopters and innovators may have already published their initial findings, leading to a natural decline in the number of new publications. Economic uncertainties and budget constraints, particularly in the wake of global events such as the COVID-19 pandemic, might have also led to reduced funding for research and development in emerging technologies, including blockchain. Additionally, companies might be shifting their focus from exploratory research to practical implementation and optimization of existing blockchain solutions, which can result in fewer academic publications as efforts concentrate on real-world application and commercialization. The initial surge in blockchain research was driven by its novelty and the excitement around its potential applications. As the technology becomes more understood and integrated into standard practices, the academic novelty diminishes, potentially reducing the number of new studies. There might also be a growing trend of integrating blockchain research with other disciplines, leading to publications being distributed across different fields and journals, which could dilute the apparent volume of blockchain-specific research within the agri-food sector.

While these factors suggest a complex interplay of reasons behind the slowdown, it is crucial to monitor the trend over the coming years to determine if it is a temporary phase or indicative of a longer-term shift in research dynamics. Understanding industry needs and aligning research goals with practical applications will be essential in sustaining academic interest and fostering continued innovation in blockchain technology for food traceability.

Of the initial 725 documents identified, a detailed analysis was conducted on 15 key documents. The selection of these documents was guided by the following criteria:

- Relevance to research objectives: only documents that directly addressed blockchain technology in food traceability were included, ensuring they aligned with the study's goals.
- Quality of the source: priority was given to peer-reviewed journals, high-impact conference papers, and authoritative reports, ensuring credibility and reliability.
- Recency: recent publications were prioritized to incorporate the latest advancements and trends in blockchain technology within the agri-food sector, providing an up-to-date perspective.
- Citation count: documents with higher citation counts were considered more influential and impactful, highlighting seminal works and widely recognized research.
- Diversity of perspectives: the selection included a variety of perspectives from different stakeholders in the food supply chain, such as technology developers, food processors, and regulatory bodies, ensuring a comprehensive understanding.
- Case study insights: papers and reports with practical case studies or empirical data on blockchain implementation in the food industry were prioritized, providing concrete examples and insights crucial for understanding real-world applications and outcomes.

By following these criteria, the selection process ensured that the most significant and relevant documents were analyzed, supporting the study's objectives and findings.

Reviewed Articles and Key Insights

Yang et al. [49] propose an innovative system for the traceability of fruits and vegetables leveraging blockchain technology to address current traceability issues. Their solution integrates blockchain and databases to ensure data immutability on the blockchain, while public data is stored in databases for improved performance and reduced blockchain load, enabling more efficient queries. Similarly, Keerthivasan et al. [50] explore BCT application in the fruit and vegetable supply chain, focusing on qualitative and social implications. They conclude that while promising, blockchain technology faces adoption challenges including expert opinions, directives, strategies, and administrative structures that can significantly hinder further development in this specific sector.

Tian [51] analyzes two categories of agri-food products: fresh produce like fruits and vegetables, and meats. Employing a combination of blockchain and RFID technologies, Tian's decentralized approach allows all parties to monitor transactions and product-related information, highlighting significant advantages and challenges compared to centralized solutions, considering social, financial, and technical aspects.

Building on previous work, Tian [52] further evolved the decentralized approach, synergistically incorporating blockchain, IoT tools, and Hazard Analysis Critical Control Point (HACCP) analysis. Morais et al. [54] propose a blockchain-based traceability system for fruit and vegetables in a "farm to fork" process with IoT, aiming to mitigate risks of poor quality and fraud while developing consensus mechanisms and smart contract models.

A solution for soy traceability using Ethereum blockchain technology with smart contracts and the Interplanetary File System (IPFS) for some data storage is introduced in the study proposed by Salah et al. [54]. This approach aims to prevent blockchain overload by utilizing associative storage space. Instead, Tse et al. [55] focus on the increasing issue of food safety in China, presenting an environmental analysis based on Political, Economic, Social, and Technological (PEST) aspects to identify challenges and opportunities related to the proposed solution.

Caro et al. [56] propose a blockchain platform named AgriBlockIoT for the agricultural supply chain, capable of integrating various IoT sensor devices and relying on publicly available blockchain implementations of Ethereum or Hyperledger.

Koirala et al. [57], Baralla et al. [58], Lin et al. [59], and Yang et al. [49] advocate for a similar framework using consortium blockchains and smart contracts. Specifically, Baralla et al. [58] and Yang et al. [49] promote the idea of reducing data stored on the blockchain using an on-chain/off-chain approach, where on-chain data are necessary for tracking and tracing a product, and off-chain data are business data, most of which are confidential and therefore encrypted.

In the "BRUSCHETTA" project, a blockchain-based application for tracing and certifying the Extra Virgin Olive Oil (EVOO) supply chain is proposed, enabling end-customers to access a tamper-proof product history, including cultivation, harvesting, production, packaging, storage, and transportation processes [60]. BRUSCHETTA leverages IoT technologies to interconnect quality control sensors operating on the blockchain. Following BRUSCHETTA, in 2022, at the 17th Iberian Conference on Information Systems and Technologies, a similar application using smart contracts and Web DApps for the same supply chain was proposed [61]. At the 2022 Arab International Conference on Information Technology, Carrefour UAE's case study and its collaboration with IBM Food Trust were presented to the committee [62].

Among the most recent documents reviewed, Gazzola et al. [63] analyze Lavazza's pilot project, which recently introduced a blockchain-tracked product on the market with the xFarm platform, highlighting the evolving landscape of blockchain application in food processing traceability.

Table 1 summarizes the main stakeholders and the specific case studies outlined in the reviewed articles.

Table 1 - Main features of the reviewed articles.

Authors (year)	Main stakeholder	Case study
Yang X, Li M, Yu H, et al (2021)	Technology developers	Fruit and vegetables
Keerthivasan E, Vignesh KR, Shinthan D, et al (2022)	Regulatory bodies	Fruit and vegetables
Tian F (2016)	Food processors	Fruit and vegetables, meats
Tian F (2017)	Technology developers	HACCP analysis
Morais R, Da Cruz AMR, Cruz EF (2023)	Food processors	Fruit and vegetables
Salah K, Nizamuddin N, Jayaraman R, Omar M (2019)	Technology developers	Grains and cereals
Tse D, Zhang B, Yang Y, et al (2017)	Regulatory bodies	Food safety in China
Caro MP, Ali MS, Vecchio M, Giaffreda R (2018)	Technology developers	None
Koirala RC, Dahal K, Matalonga S (2019)	Technology developers	None
Baralla G, Ibba S, Marchesi M, et al (2019)	Food processors	Food supply chain in Sardinia Region (Italy)
Lin Q, Wang H, Pei X, Wang J (2019)	Technology developers	None
Arena A, Bianchini A, Perazzo P, et al (2019)	Food processors	Olive oil

Fernandes MA, Cruz EF, Da Cruz AMR (2022)	Food processors	Olive oil
Eletter SF, Elrefae GA, Yasmin T, et al (2022)	Technology developers	Carrefour UAE supply chain
Gazzola P, Pavione E, Barge A, Fassio F (2023)	Food processors	Lavazza supply chain

BUSINESS CASE STUDIES

In the dynamic landscape of the food processing industry, blockchain technology stands at the forefront of revolutionizing traceability and establishing a culture of transparency and trust. This section delves into an array of practical blockchain applications within the agri-food supply chain, featuring compelling business cases that illuminate the path towards enhanced traceability and transparency. The exploration encompasses a spectrum of companies, i.e. Placido Volpone S.r.l., Spinosa S.p.A., Bofrost Italia, Carrefour Italia, Lavazza, and the innovative startup TATTOO WINE, each demonstrating pioneering efforts in leveraging blockchain for varied yet unified objectives.

These case studies collectively showcase the diverse ways in which blockchain technology can significantly enhance transparency, trust, and operational efficiency within the agri-food supply chain. From improving traceability at every stage of the production process to increasing consumer engagement and confidence through verifiable data, each case illustrates the tangible benefits that blockchain can bring to different aspects of the industry. The following subsections will delve into the specifics of each business case, providing detailed analysis and quantifiable metrics that demonstrate how these improvements have been realized and the impact they have had on overall supply chain management.

Placido Volpone Winery and Blockchain Implementation

Placido Volpone S.r.l., a venerable winery with origins in 1890, has taken a pioneering step by incorporating blockchain technology to notarize data for its "Falanghina" wine's production chain, a first in the wine industry. This initiative, spurred by a desire to combat counterfeiting and ensure product authenticity, was realized in collaboration with Ernst & Young (EY) and the tech startup Ezlab. The move to blockchain was part of a broader transformation that began in 2008, transitioning from personal grape production to commercial winemaking, and was further accelerated by a counterfeit incident in 2016, highlighting the need for a more secure system [64].

The "Wine Blockchain" project transitioned through three phases:

1. Evaluation Phase:
   This initial phase, lasting about three months, involved detailed assessments of winery processes, mapping the production chain, and identifying the necessary tools. The focus was on internal production stages, excluding post-sale phases to minimize complexity. The chosen product for pilot certification was the Falanghina wine. Manual data collection methods were used initially, with plans for subsequent digitalization.
2. Adoption of AgriOpenData:
   The second phase involved the integration of AgriOpenData, a cloud-based data management platform developed by Ezlab. This platform facilitated the digitization of various aspects of the winery's operations, from cultivation to production processes. AgriOpenData helped streamline documentation, compliance with legal requirements, and real-time data management, significantly reducing bureaucratic workload and improving data accessibility.
3. Development Phase:
   The final phase focused on developing the blockchain solution. This included creating smart contracts, notarizing data on the blockchain, and designing a consumer-facing landing page. The solution used both Ethereum and Bitcoin blockchains, chosen for their respective advantages in transaction speed and data immutability. Data from vineyard activities to bottling were accurately recorded, ensuring comprehensive traceability and quality control.

The technical aspect of the blockchain implementation involved using both the Ethereum and Bitcoin blockchains. Initially, the Ethereum blockchain was used for its faster transaction speeds and lower costs. However, Bitcoin's blockchain was later adopted due to its superior immutability and security features. Data was collected and managed through the AgriOpenData system, ensuring that all production processes, from vineyard activities to bottling, were accurately recorded and verified. This included detailed tracking of processes such as pruning, fertilization, harvesting, fermentation, and bottling, ensuring comprehensive traceability and quality control.

The blockchain implementation involved several key components, each contributing to the system's overall effectiveness. Data gathering was the initial step, where information was collected from the field using both manual and automated methods, ensuring that comprehensive data was captured and sent downstream for further processing. The AgriOpenData platform played a crucial role in digitizing and automating data tasks across the supply chain, streamlining processes and enhancing efficiency. This data was then registered on the blockchain via the platform AgriChain, which provided transparency and allowed for varying levels of privacy depending on the type of information being recorded. As data entered the blockchain, it was stored as an immutable block, with each node certifying the entry to maintain the integrity and security of the information. To enhance the user experience, web properties were developed, enabling end-users to access the information through responsive interfaces, thereby improving customer communication and engagement.

The implementation of blockchain technology in Placido Volpone led to several significant outcomes. First, the winery experienced a 3.5% reduction in production costs, primarily due to improved efficiency in data management and a 10% decrease in manual bureaucratic tasks, which lowered variable labor and administrative costs. Moreover, the adoption of blockchain allowed Placido Volpone to increase the price of its products by 6.2% per bottle, a direct result of the enhanced transparency and authenticity that the technology provided. This price adjustment, coupled with an improved market perception, contributed to a return on investment (ROI) of 14.53%. Additionally, the market expansion facilitated by blockchain technology led to higher sales volumes and increased revenue. The improved transparency and product authenticity significantly boosted consumer confidence, demonstrating a clear willingness among customers to pay a premium for enhanced traceability and authenticity.

The primary challenge of this project was integrating the blockchain technology within the existing processes, ensuring all relevant data was accurately recorded and managed. However, the advantages, such as improved transparency, enhanced consumer trust, and operational efficiency, outweighed these challenges. The initiative served as a compelling model for the broader food processing industry, showcasing the tangible economic benefits and enhanced market perception achieved through blockchain adoption.

Spinosa S.p.A. and Blockchain in Dairy Industry

Spinosa S.p.A., a family-run dairy company famous for Campana DOP buffalo mozzarella, has integrated blockchain technology to ensure complete traceability of its products from farm to table. Starting as a small local dairy and evolving into an international brand, Spinosa's use of blockchain was driven by a need for transparency and certification, especially important as it expanded globally. The company utilizes QR codes on packaging, leading to a dedicated webpage where consumers input a batch code to access detailed information about the product's lifecycle, from breeding to distribution, all adhering to the Consortium for the Protection of Buffalo Mozzarella Campana DOP standards.

The blockchain project completed in 2019 aimed to make the entire production process of its mozzarella di bufala fully traceable. Each DOP product package includes a QR code that consumers can scan to visit a dedicated webpage. Consumers then enter the batch code from the packaging to access comprehensive information about the product, including details on breeding, processing, and distribution, as well as compliance with quality and safety standards.

The blockchain implementation integrates several key components to ensure comprehensive traceability and transparency. First, data is gathered from various sources throughout the production process, including breeding, milk collection, processing, quality assurance, and distribution. This information is then managed and entered into the Ops Chain Food Traceability Platform, developed by EY on Ethereum architecture, which supports detailed data management and enhances transparency at every production stage. To facilitate consumer access to this information, QR codes are pre-printed on the packaging. These codes direct consumers to a webpage where they can input the batch code to retrieve specific product details. Additionally, the data is certified on the blockchain, leveraging the Ethereum blockchain for its robust transaction handling and data management capabilities. The implementation is further optimized by the Polygon layer framework, which improves scalability, speed, and cost-efficiency for each transaction, ensuring both the immutability and transparency of the data.

Information is collected from various sources, including breeding, milk collection, processing, quality assurance, and distribution. The Ops Chain Food Traceability Platform, developed by EY and based on Ethereum architecture, allows for detailed data entry and management, ensuring transparency at each production stage. QR codes are pre-printed on packaging and lead to a general webpage, where consumers input the batch code to access specific product information. Data is securely stored on the blockchain, ensuring immutability and transparency. The Ethereum blockchain is used for its advanced capabilities in handling transactions and data management, while the Polygon layer enhances scalability, speed, and cost-efficiency of each transaction.

Breeding information includes the geographic location of the farms, milking dates, animal breeds, and milk contribution percentages. Arrival at the facility details include transport dates, vehicle specifications, and times for start and end of milking and pasteurization. Processing data on pasteurization temperatures and durations, coagulation details, and maturation times are entered. Parameters such as organoleptic properties, chemical contents, and microbiological data of the final product are included. Distribution records transport temperatures and departure dates from the facility.

Consumers can verify each production process step, confirmed by blockchain certification. Each process entry has a "Blockchain certified" tag, allowing consumers to trace the timestamp and smart contract address for verification on Polygonscan.

The blockchain implementation has significantly improved transparency, consumer trust, and compliance with quality standards. By providing end-to-end traceability, Spinosa has enhanced its brand reputation and market competitiveness. The initiative demonstrates how blockchain can revolutionize the dairy industry, ensuring product authenticity and boosting consumer confidence.

Overall, Spinosa S.p.A. adoption of blockchain technology highlights its potential to provide comprehensive traceability, ensuring high standards of quality and transparency, and setting a new benchmark in the dairy sector.

Bofrost Italia's Blockchain Implementation for Frozen Food Traceability

Bofrost Italia has harnessed blockchain technology to revolutionize transparency and quality assurance in the frozen food supply chain. Collaborating with EY on a blockchain solution via the EY OpsChain Traceability platform, Bofrost initiated this innovative approach with Nordic Cod Fillets and Artichoke Heart Wedges, focusing on verifying supplier actions and guaranteeing product integrity. This system enables consumers to trace the journey of their food by scanning a QR code, aligning with increasing demands for product transparency. The blockchain application process follows the same logic as the Spinosa project.

Consumers can scan a QR code on the packaging and enter the batch code to access detailed information about the product's origin, quality, and safety. The information provided includes various stages of the supply chain:

1. Fishing: details about the fishing vessel, fishing gear, MSC certification code for sustainable fishing, geolocation, fishing period, species description, and habitat are recorded. This ensures that sustainable fishing practices are followed and verified.

2. Freezing: data regarding the freezing date, temperature, and arrival date at the port are captured. It is critical that no more than six hours pass from fishing to freezing and that the temperature is below -18°C to ensure product quality.
3. Packaging: from the port to the bofrost facility, temperatures are monitored during transport and unloading. Consumers can view temperature control data and the date of product intake at the facility.
4. Storage: storage temperatures are closely monitored, with products typically stored at around -26°C. Each arrival is checked, and temperature data is recorded to maintain the integrity of the cold chain.
5. Quality control: bofrost makes chemical and microbiological control data publicly accessible, including detailed quality reports. Consumers can download reports signed by quality control managers, containing organoleptic analysis, decomposition analysis, and microbiological and chemical analysis.
6. Delivery: vehicles used for home delivery are equipped with thermometers, allowing real-time monitoring of transport temperatures. This ensures that the product remains within safe temperature ranges during delivery.

The blockchain implementation utilized the Ethereum-based EY OpsChain Traceability platform. This platform leverages several key components and mechanisms, as summarized in Table 2.

Table 2 - Key components and mechanisms of Bofrost Italia's blockchain implementation for frozen food traceability.

Component	Description
Blockchain Architecture	The system is built on Ethereum, known for its robust smart contract functionality. Ethereum was chosen for its ability to handle complex transactions and support decentralized applications.
Consensus Mechanism	Ethereum uses the PoS consensus mechanism, which is energy-efficient and ensures data immutability. This mechanism was preferred over PoW due to its lower energy consumption and faster transaction speeds.

Type of Data Processed and Stored	The data includes detailed records of fishing practices, freezing data, packaging information, storage conditions, quality control reports, and delivery temperatures. Each data point is critical for maintaining transparency and integrity of the supply chain.
Points of Data Interaction	Data interactions occur at multiple points in the supply chain: o fishing data is recorded by the fishing vessel and uploaded to the blockchain; o freezing data is captured at freezing and during transportation to the port; o packaging and storage data are logged at the Bofrost facility; o quality control data is entered by quality assurance teams; o delivery data is recorded by sensors in delivery vehicles.

The dashboard used by Bofrost employees for data entry is designed to be user-friendly, enabling staff with varying levels of IT proficiency to input information accurately. The interface supports data entry for raw material batches, finished product batches, and quality control checks. This data is then published and notarized on the blockchain, reinforcing transparency and accountability.

By providing a detailed account of food products' lifecycles, Bofrost not only meets the growing consumer demand for information and authenticity but also establishes a new benchmark in the industry for transparency and trust. This case study serves as a model for leveraging digital innovation to enhance the integrity and reliability of food supply chains.

Carrefour Italia: Trailblazing Blockchain in Retail

Carrefour Italia, a leading player in the Italian Grande Distribuzione Organizzata (GDO), was the first to implement blockchain technology for food traceability, starting with its own-brand chicken.

The complexity of its supply chain presented significant challenges, but the implementation aimed to enhance transparency, combat counterfeiting, and ensure product authenticity. This initiative, part of the EY OpsChain Traceability program, became operational in September 2018 and involved 29 farms, 2 feed production plants, and 1 slaughterhouse. Carrefour Italia announced plans to extend blockchain traceability to its citrus fruit supply chain next.

The blockchain system used by Carrefour enables consumers to access detailed information about the product via a QR code on the packaging. This includes the place and method of farming, the name of the farmer, feed used, antibiotic-free status, slaughtering location, and transport methods. This system ensures that all actors in the food chain, including producers, processors, and distributors, can provide accurate, immutable traceability data for each product batch.

According to Giovanni Panzeri, Director of Carrefour Italia's own-brand products, significant benefits were observed just weeks after the project's launch. Panzeri reported a doubling of revenues for blockchain-tracked chicken products and an increase in visits to the product's QR code-linked webpage, demonstrating consumer demand for higher quality and transparency [62]

While relational databases have traditionally been used for managing supply chain data, they lack the decentralized, immutable, and transparent nature of blockchain technology. Relational databases rely on a centralized server architecture, which can be a single point of failure and is prone to tampering. In contrast, blockchain technology leverages a distributed ledger system where data is stored across multiple nodes, ensuring redundancy, security, and immutability. The implementation of blockchain technology at Carrefour involved significant technical details that improved overall supply chain performance, as summarized in Table 3.

Table 3 - Key components and mechanisms of Carrefour Italia's blockchain implementation.

Component	Description
Blockchain Infrastructure	Carrefour used IBM Food Trust, a blockchain-based platform, to enhance supply chain transparency, traceability, and trust. IBM Food Trust ensures data accuracy and immutability by leveraging distributed ledger technology [62].
Consensus Mechanism	IBM Food Trust employs a permissioned blockchain model, relying on a known group of

	validators to confirm transactions. This enhances efficiency and reduces computational load compared to public blockchains.
Type of Data Processed and Stored	The data includes detailed records of farming practices, feed information, antibiotic-free certification, slaughtering details, and transportation conditions, ensuring full traceability from farm to table.
Smart Contracts	Smart contracts automate many aspects of supply chain management, reducing the need for intermediaries, minimizing human error, and ensuring transactions are executed as programmed [62].
Data Management and Integration	IoT devices and sensors provide real-time data collection on critical parameters such as temperature, humidity, and location during transportation. This data is automatically notarized on the blockchain and managed by advanced systems [62].

Data interactions are integral to the supply chain, occurring at multiple critical points. The process begins with farming, where details about farming practices are recorded, including the location, methods used, and farmer information. Next, information regarding the feed provided to the animals and the absence of antibiotics is documented to ensure compliance with safety standards. As the supply chain progresses, data on the slaughtering process, including both the location and methods employed, is captured to maintain traceability. During transportation, real-time conditions such as temperature and humidity are monitored using IoT devices and sensors, ensuring that products are maintained under optimal conditions. Finally, consumers can access this comprehensive data via QR codes on the packaging, which enhances transparency and builds trust in the product's journey from farm to table.

The implementation of blockchain technology led to significant improvements across several key performance metrics. Efficiency was notably enhanced, as the automated and immutable nature of blockchain records reduced both the time and cost associated with quality assurance and compliance checks. In terms of traceability, the ability to track the origin and journey of products was drastically improved, enabling what once took weeks to now be accomplished within seconds. This rapid traceability allows for a quicker response to any potential food safety issues, thereby improving overall safety measures. Moreover, the increased transparency and the availability of detailed product information significantly boosted consumer trust and loyalty, which in turn contributed to higher sales [62].

This implementation allowed Carrefour to utilize an efficient dashboard for monitoring supply chain developments, enhancing quality control and product assurance. The initiative not only boosted sales but also elevated customer perception of Carrefour's own-brand products. The strategic use of blockchain has streamlined processes and ensured better compliance and monitoring across the supply chain.

By integrating blockchain technology, Carrefour Italia has set a new benchmark in retail transparency and food safety, meeting consumer demands for detailed product information and establishing a model for future digital innovation in the industry.

Lavazza S.p.A.: Infusing Blockchain into Coffee Production

In late 2022, Lavazza introduced "Noble Vulcano," a special blend under its "1895 Coffee Designers" brand, utilizing blockchain to assure sustainability and traceability [63, 65]. By integrating xFarm platform functionalities with blockchain technology, Lavazza provides transparent insights into the entire coffee production process. This includes detailed climatic and soil parameters collected by xFarm team members in Brazil, enhancing the quality metrics and sustainability practices of coffee farming. The project, aimed at harnessing cutting-edge IoT and blockchain solutions, offers a comprehensive view of the coffee supply chain, from cultivation to consumer, paving the way for a new standard in the coffee industry's digital transformation.

For the implementation of the project, Lavazza decided to integrate the xFarm platform with blockchain technology. XFarm, designed to simplify the management of agricultural activities, enables users to fully engage with agriculture 4.0 by facilitating digital interaction with their farms. The platform integrates functions dedicated to cultivation, logistics, bureaucracy, and agricultural machinery management, making data accessible at various stages of the coffee production process.

In January 2021, two xFarm team members were dispatched to Brazil to set up sensors and equipment for gathering extensive climatic data on air and soil, essential for calculating specific Key Performance Indicators (KPIs). This mission allowed for a thorough analysis of the selected KPIs' impact on process quality. The xFarm team provided training to Brazilian farm operators on the platform's use, ensuring accurate data collection and entry.

The Fazenda farms, already utilizing a System Applications and Products in Data Processing (SAP) tool for tracking coffee processing activities, integrated additional sensors for enhanced data collection, including rain measurement, air humidity, temperature sensors, and cameras. Despite challenges such as limited cellular connectivity, local IoT solutions were implemented to overcome these obstacles. The project's pilot phase involved installing sensors in fields cultivating the selected coffee varieties, Catucai and Arara, chosen based on harvest quality assessments.

The blockchain used for KPI recording in this project is the new-generation Algorand, a Pure Proof-of-Stake (PPoS) network known for solving the blockchain trilemma of security, scalability, and decentralization. Both periodic KPIs, recorded every two weeks, and one-shot KPIs, entered manually, are stored on the blockchain, ensuring transparency and immutability of data.

Lavazza utilizes Algorand's PPoS consensus mechanism, which enhances the security, scalability, and decentralization of the network. Algorand’s smart contracts thus allow developers to create decentralized applications with instant finality. This choice allows for a robust and efficient verification of transactions, suitable for the extensive data requirements of the coffee production chain.

The data processed and stored on the blockchain encompasses a comprehensive range of information critical to maintaining product quality and traceability. This includes climatic data, such as temperature, humidity, precipitation, and wind speed, which are essential for understanding and managing environmental conditions. Soil parameters, including moisture and nutrient levels, are also recorded to ensure optimal growing conditions. Operational data is also tracked, covering key stages like harvesting dates, transportation details, drying and fermentation processes, and specific roasting specifications. Additionally, quality metrics, such as quality scores, sensory evaluation results, and adherence to sustainability standards, are documented to guarantee that the products meet the highest quality and ethical benchmarks.

The data interaction points within Lavazza's blockchain system are extensive, ensuring a thorough and integrated approach to quality and traceability. IoT sensors play a crucial role by collecting real-time data on environmental conditions, which feeds into the system for continuous monitoring. The integration of farm management systems, such as xFarm and SAP tools, allows for comprehensive management of farm operations, ensuring that all aspects of the agricultural process are meticulously tracked. Quality control systems are employed to record detailed sensory and chemical analysis data, maintaining high standards throughout the production process. Additionally, transport monitoring is conducted to track shipping conditions as the product moves from Brazil to Italy, ensuring that the coffee is transported under optimal conditions to preserve its quality.

The final consumer interface, developed in collaboration with Publicis Sapient, allows consumers to access detailed traceability information by entering a batch ID from the packaging. This mobile-first solution provides insights into each step of the coffee's journey, from growth conditions and harvesting to drying, quality assessments, transport, and roasting.

Lavazza's blockchain initiative not only enhances transparency and sustainability in coffee production but also educates consumers and strengthens their trust in the brand. The blockchain's integration with IoT and real-time data management systems exemplifies a forward-thinking approach to supply chain transparency and sustainability in the food industry [63].

TATTOO Wine: Digitizing the Wine Market

Blockchain Wine Ltd., founded in 2018 and based in Singapore, collaborated with EY OpsChain to develop the TATTOO Wine marketplace. This initiative aims to promote and sell premium wines globally, with a specific focus on the rapidly growing markets in China, Japan, South Korea, Thailand, and Singapore, where the consumption of European wines is increasing significantly.

The project resulted in the creation of a revolutionary e-commerce platform that leverages blockchain technology for wine supply chain traceability and tokenization. The system operates on the public Ethereum blockchain, ensuring decentralized control, which enhances trust in data integrity and facilitates the easy and cost-effective addition of new partners to the network. One of the unique aspects of the project is the tokenization of wine purchases and sales, allowing for the planning and monitoring of shipments, storage, and distribution.

Supported by the EY OpsChain platform, consumers can purchase premium wines in the form of digital tokens that uniquely identify each bottle within registered production batches on the Ethereum blockchain. These tokens (representing uniquely identified wine bottles) are exchanged for fungible TATTOO Tokens, which signify the payment made with traditional currency. The blockchain includes management tools that enable distributors and consumers to use tokens to place orders directly on the TATTOO platform, allowing real-time tracking of shipments and customs clearance processes. The tokenization of bottles allows for comprehensive supply chain data collection, enabling the verification of digital processes such as procurement automation and inventory orders. Each wine bottle is "tattooed" with its unique QR code, providing access to detailed information about the production process.

For rare wines, an NFC tamper-proof seal is included within the wine cap. Once the bottle is opened, the chip is damaged, and the information can no longer be read or written, providing an additional layer of protection against counterfeiting. Figure 33 visually illustrates the idea behind EY's project.

The TATTOO Wine marketplace uses the Ethereum blockchain, which supports the creation and management of digital tokens representing individual wine bottles. This decentralized ledger ensures that no single party has control over the data, enhancing transparency and trust.

Ethereum's consensus mechanism, PoS, is utilized to validate transactions and ensure the integrity of the blockchain. This mechanism involves validators staking their Ether (ETH) to propose and validate new blocks, providing security and decentralization. Furthermore, smart contracts are an integral part of the Ethereum network, allowing developers to create self-executing agreements.

The blockchain in TATTOO Wine’s system is designed to store a diverse range of data that is crucial for maintaining traceability and ensuring authenticity. This includes detailed wine production data, capturing information about the wine's origin, the production process, and various quality metrics. Additionally, digital ownership tokens are created to represent the ownership of specific wine bottles, providing a secure and verifiable record. The system also records real-time tracking information for shipments and customs processes, ensuring that the movement of goods is transparent and traceable. For rare wines, data related to the tamper-proof NFC seals is stored, further ensuring the authenticity of these premium products. Interaction with the blockchain occurs at several key points. During purchase and sales transactions, consumers and distributors use digital tokens to place orders and track their purchases. The blockchain also captures detailed records during the production and bottling processes, ensuring that every step is documented. Moreover, real-time data related to shipping and customs clearance is recorded, guaranteeing transparency and traceability throughout the supply chain.

This comprehensive strategy highlights the potential of blockchain technology to enhance product authenticity and consumer trust in the wine industry, setting a new standard for digital transformation in supply chain management.

CHALLENGES AND ADVANTAGES IN THE APPLICATION OF BLOCKCHAIN TECHNOLOGY

The selection of a particular type of blockchain and the evaluation of suitable combinations such as "blockchain and database" [49], Ethereum or Hyperledger applications [56], dual-chain solutions [57], or Blockchain for IoT [53, 60] are intimately dependent on the specific characteristics of the application domain. This choice involves a detailed pre-evaluation focusing on qualitative and technical aspects, drawing on significant insights from literature.

The transition to blockchain in the food processing industry is fraught with challenges:

- Resistance to Adoption: Blockchain disrupts established practices, potentially leading to stakeholder pushback. The digital transformation introduces complexity in a sector with numerous actors and layered responsibilities, complicating the management of technological change.
- Financial Barriers: The substantial initial investment required for blockchain implementation includes the costs of developing or purchasing blockchain platforms, integrating them with existing systems, and training staff. Additionally, ongoing costs for maintaining the blockchain infrastructure can be prohibitive, especially for small and medium-sized enterprises (SMEs) in the food industry.
- Operational Challenges: Manual data entry can be time-consuming and prone to errors. The accuracy and reliability of blockchain data depend heavily on the integrity of the data entered. Operators might resist adopting new procedures requiring additional effort without immediate and obvious benefits. Moreover, integrating blockchain with existing ERP (Enterprise Resource Planning), CRM (Customer Relationship Management), and MES (Manufacturing Execution Systems) can be complex and costly.
- Cultural Resistance: Many operators and managers might be sceptical about the benefits of blockchain, viewing it as a trendy but unnecessary tool. Convincing stakeholders of the long-term benefits and securing their buy-in is essential but challenging. Additionally, the

willingness of companies to pay more for blockchain-enhanced traceability remains uncertain, as the perceived benefits must outweigh the costs.

- Digital Divide: The financial and resource-intensive nature of implementing blockchain traceability systems exacerbates the digital divide between industrialized and developing nations, raising questions about the technology's cost-effectiveness and accessibility.

Conversely, blockchain technology heralds numerous advantages for the agri-food supply chain:

- Decentralization: Its decentralized nature eliminates reliance on central servers, mitigating food security risks and fostering collaboration.
- Security, Efficiency, and Fraud Prevention: The technology's security, efficiency, and fraud prevention capabilities are vital in maintaining food quality and ensuring consumer safety.
- Failure Detection: Blockchain's ability to promptly detect system failures can significantly reduce food waste and losses, enhancing the sustainability of agri-food supply chains.
- Interoperability: Developing common standards and protocols is crucial for effective data sharing and collaboration among various blockchain and digital traceability systems.
- IoT as a Developing Technology: The IoT should be regarded not as an emerging technology but as a developing one with significant potential in automating data entry. Automating data entry through IoT devices can address one of the main reasons for digitalization failures in companies, which is the reliance on manual data entry. According to a study by McKinsey [66], 70% of digitalization efforts fail due to issues related to manual data entry. The integration of IoT with blockchain can therefore enhance the accuracy and reliability of data, making digital processes more efficient and less prone to human error.

Blockchain technology, while often perceived as a buzzword, offers substantial business potential when applied thoughtfully within the food processing industry. This potential is realized through several key avenues:

- Enhanced Transparency and Trust: Blockchain's inherent transparency can significantly enhance consumer trust by providing verifiable, tamper-proof records of a product's journey from farm to table. This can lead to increased brand loyalty and higher sales, as consumers are willing to pay a premium for products they trust.

  To substantiate this claim, several studies and market surveys have indicated a growing consumer demand for transparency in the food supply chain. For instance, a 2022 survey by

IBM found that 49% of consumers are willing to pay a premium - an average of 59% more - for products branded as sustainable or socially responsible [67]. Additionally, the study highlighted that 62% of consumers are willing to change their purchasing habits to help reduce environmental impact, further demonstrating a market-driven incentive for companies to invest in blockchain technology for traceability [67]. Similarly, a report by the Food Marketing Institute (FMI) and NielsenIQ revealed that consumers increasingly prioritize information about product origins and ethical sourcing when making purchasing decisions. The report showed that 64% of shoppers would switch from a brand they usually buy to another brand that provides more in-depth product information, beyond basic nutrition facts [68]. Further supporting this trend, a study found that the implementation of a blockchain food traceability system positively impacts consumers' affective brand commitment and their motivation to pay a premium price for traceable food products [69]. Additionally, a scoping review indicated that consumer willingness to pay for traceable food products is influenced by socio-demographic characteristics and highlights the importance of transparency in the food supply chain [70].

The real business cases have also demonstrated the economic benefits of enhanced traceability. For instance, as abovementioned, Carrefour reported a significant increase in sales for products tracked using blockchain technology. This example illustrates that when consumers have access to transparent and reliable information about product origins, their trust and willingness to pay for these products increase.

- Operational Efficiency: Blockchain can streamline various processes within the supply chain, reducing inefficiencies and cutting costs. By automating data recording and verification through smart contracts, businesses can minimize human errors and reduce the need for intermediaries. This operational efficiency can lead to cost savings and improved profit margins.

- Market Differentiation: Companies that adopt blockchain technology can differentiate themselves in a competitive market. By leveraging blockchain for enhanced traceability and quality assurance, businesses can create unique selling points that set them apart from competitors. This differentiation is particularly valuable in markets where consumers prioritize food safety and ethical sourcing.

- Regulatory Compliance: Blockchain can assist companies in complying with stringent food safety regulations by providing accurate and immutable records of production processes. This not only ensures compliance but can also simplify audits and reduce the risk of regulatory penalties.

- Long-Term ROI: While the initial investment in blockchain technology can be high, the long-term return on investment can be substantial. Improved supply chain transparency and efficiency, combined with increased consumer trust, can drive higher sales and market share. Additionally, blockchain can open new revenue streams through data monetization and enhanced product offerings.

Cybersecurity remains a critical issue, with blockchain's encryption and decentralization offering intrinsic security measures. However, protecting sensitive information and preventing cyber-attacks require additional safeguards. Existing solutions such as backup servers provide adequate data safety for many companies, making the distributed nature of blockchain registers less of a winning feature. Instead, the true advantage of blockchain may lie in its immutability - the impossibility to alter the blocks once they are recorded. This aspect of blockchain ensures data integrity and can be particularly valuable for companies' IT departments, providing a higher level of trust in the recorded information.

The transparency afforded by blockchain could engage consumers more deeply by allowing them to trace the origin and quality of food, emphasizing the role of education and community awareness in fostering technology acceptance. Navigating the evolving regulatory landscape and ensuring compliance with laws governing blockchain and the agri-food supply chain are also key to successful implementation.

Looking forward, the integration of blockchain with emerging technologies like artificial intelligence promises to advance traceability and supply chain management in the agri-food sector further, pointing toward a future where process efficiency and security are significantly enhanced.

By focusing on these business potentials, companies can make a compelling case for the adoption of blockchain technology, addressing both the practical benefits and strategic advantages it offers in the food processing industry.

Comparative Analysis of Blockchain and Existing Managerial Software

Blockchain technology, while offering unique advantages, is often perceived as a trendy solution that might not always address the core needs of efficient traceability. To understand this perception, it is crucial to compare blockchain with existing managerial software such as ERP, CRM, and MES, which have been in use for many years.

ERP, CRM, and MES systems have been designed to integrate seamlessly, enabling a natural flow of information across different departments and stages of production. These systems utilize frontier tables and standardized protocols to ensure data consistency and accessibility. For instance, an ERP system can manage inventory levels, while MES tracks production processes, and CRM handles customer interactions and feedback. Together, they provide a comprehensive traceability solution that is both efficient and reliable.

These managerial systems are capable of ensuring high levels of traceability by sharing and synchronizing data in real-time. They allow companies to monitor and trace products throughout the supply chain without the need for additional technologies. The integration of these systems ensures that data from various sources is collated and utilized to enhance transparency and accountability.

Given the robust capabilities of ERP, CRM, and MES, blockchain may not be perceived as a necessary solution for enhancing traceability. These systems already provide a structured and efficient means of managing data flow and ensuring traceability. Blockchain, while adding an additional layer of security and immutability, might be seen as an over-engineered solution, particularly for low-value items or scenarios where existing systems are already effective.

However, blockchain's decentralized nature, combined with its immutability and security features, offers unique benefits that can complement existing systems. For example, in cases where data integrity and prevention of tampering are paramount, blockchain can provide an additional layer of trust. Its ability to create a permanent, tamper-proof record of transactions can be particularly valuable in high-stakes environments where regulatory compliance and data verification are critical.

Thus, while ERP, CRM, and MES systems provide comprehensive solutions for traceability, blockchain technology offers distinct advantages in terms of security and data integrity. Understanding the specific needs of the industry and the limitations of current systems can help determine when and where blockchain can add the most value.

GUIDELINES FOR DESIGNING A TRACEABILITY SYSTEM FOR THE FOOD PROCESSING INDUSTRY

Designing a traceability system for the food processing industry requires establishing a standard reference model that addresses the complexities of the supply chain. This process involves a detailed analysis of the supply chain, including actors, processes, resources, and data flows, to ensure seamless traceability. Implementing a unified approach helps overcome communication barriers between developers and users by employing interviews and collaborations to identify system requirements. This leads to a methodological framework that utilizes a formalized language for clear business management support, setting the stage for the application of these specifications in blockchain system design and eventual translation into executable code.

Business Process Modeling (BPM) is crucial for understanding and supporting information systems, as highlighted by de Oca et al. [71]. BPM involves an in-depth "farm to table" analysis to identify necessary data and responsible divisions, incorporating sensors for data collection. A key feature is the system's ability to monitor data at both intra-company and inter-company levels, enhancing business operations and trust among partners, as discussed by Corallo et al. [3].

Business process modeling, used for business process improvement and reengineering [72], represents processes within an organization and their interactions. It serves as a mechanism for describing current or future business processes with tools like ADONIS, ARIS, and MS Visio aiding in model development [73]. These tools facilitate the systematic development of models to meet specific requirements, thereby enhancing business process management [74].

Simplifying the Traceability System Design

The design of an effective traceability system for the agri-food sector should include guidelines for certification stages, production process mapping, and blockchain data integration. Understanding the diversity within organizational structures is crucial for precise planning and outcome definition. This demands collaboration between technology and agri-food experts.

Integrating principles from ARIS (Architecture of Integrated Information Systems) architecture, a business process modeling framework, a business process model can simplify complexities into manageable views. ARIS, developed by August-Wilhelm Scheer, is a comprehensive tool for analyzing, designing, implementing, and controlling business processes. It provides a structured approach to view and model various aspects of an organization, facilitating better understanding and management of business processes (Scheer, 2000). To address model intricacies, the business process model can be segmented into single views - Organizational, Functional, Product, Data, and Process - as shown in ARIS House [75] (see Figure 2). Each view utilizes specific diagrams and rules for a comprehensive reassembly of necessary information, relationships, and resources for each process.

The **Functional View** breaks down business processes into hierarchical functions, depicted through function trees. This includes modeling IT applications supporting business functions in "Application

System Type Diagrams", key for blockchain data tracking communication between company IT systems.

The **Organizational View** charts the organizational structure to detail roles, responsibilities, and workflows, reflecting the company's hierarchy and operational flows, crucial for process modeling accuracy.

The **Data View** concentrates on structuring and utilizing information within the organization, using Entity-Relationship Models (ERMs) to map key data elements and their interrelations, pivotal for establishing a blockchain-based traceability system.

The **Output View** illustrates the flow from raw materials to finished goods, marking stages where traceability data should be captured for blockchain ledger inclusion.

Finally, the **Process/Control View** uses business process modeling and notation for detailed representation of organizational operations, informing smart contract design for the blockchain system. This is complemented by several diagrams, including Function Allocation Diagrams (FADs), which detail resource allocation and responsibilities within process stages, and Event-Driven Process Chain (EPC) diagrams, which model the flow of events and functions in business processes, enhancing understanding of blockchain's potential for transparency and verifiability.

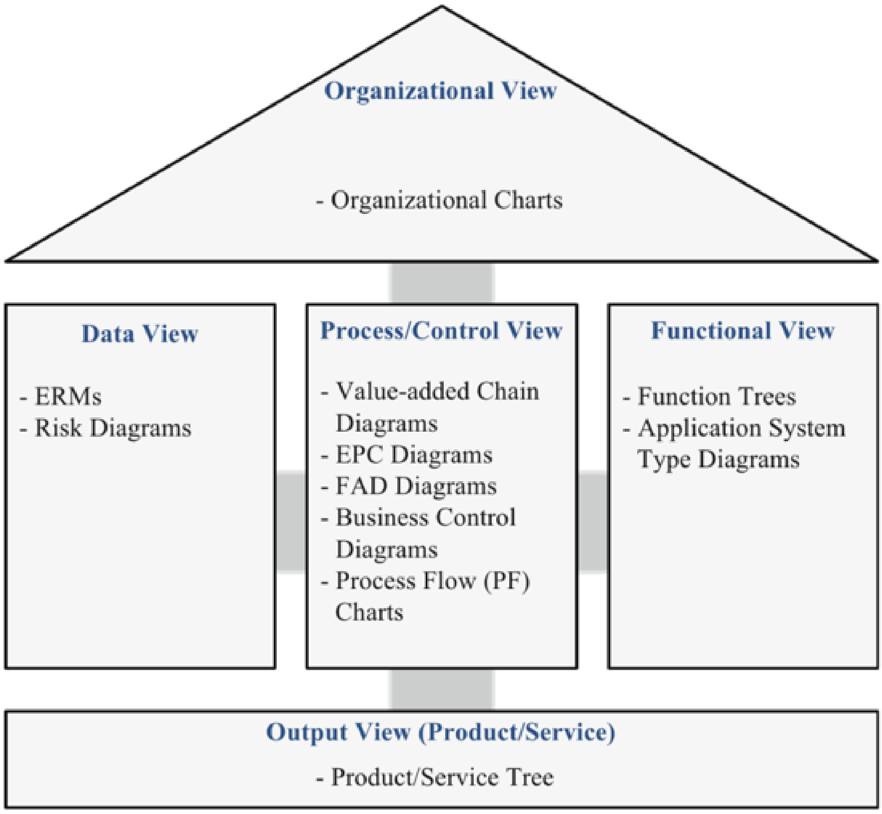

Figure 2 - The Different Views of "ARIS House" [75].

The design of an effective traceability system for the agri-food sector involves integrating various perspectives to create a unified system for process chains. Analysing multiple entities in the FVC offers a comprehensive view of process integration, essential for strategic coherence and establishing effective traceability systems. This integration enhances traceability and ensures that stakeholders have access to transparent and verifiable data.

Implementing a "blockchain + database" methodology helps differentiate between data stored on-chain for transparency and off-chain for privacy. This approach ensures that sensitive information remains secure while maintaining the transparency and immutability of the blockchain. The key components of a traceability system are outlined in Table 3 [53].

Table 3 - Key components of a traceability system and their descriptions.

Component	Description
Organizations and Roles	Clearly define the entities within the supply chain, including their responsibilities and roles, ensuring each step of the process is transparent and accountable.
Products and Tracking	Outline how products are identified and tracked from raw materials to finished goods, ensuring each product's journey is documented accurately, maintaining integrity and traceability.
Activities and Measurements	Describe how activities and measurements (e.g., temperature, pH levels) are recorded and linked to specific processes, ensuring data accuracy and reliability.
Input and Output Lots	Track the flow of materials through input and output lots, capturing every stage in the production process to maintain a clear view of the product lifecycle.

This approach ensures the integration of blockchain technology into the traceability system is both manageable and effective. It enhances the system's usability across the food value chain, ensuring data privacy where needed and transparent traceability where possible. This ultimately leads to improved product quality and increased consumer trust.

Expected Outcomes for a Blockchain-based Traceability System in the food processing industry

Following the modeling considerations and deriving the requirements for a blockchain-based traceability system, experts in computing within the field are equipped with the necessary tools to develop an architecture as depicted in Figure 3.

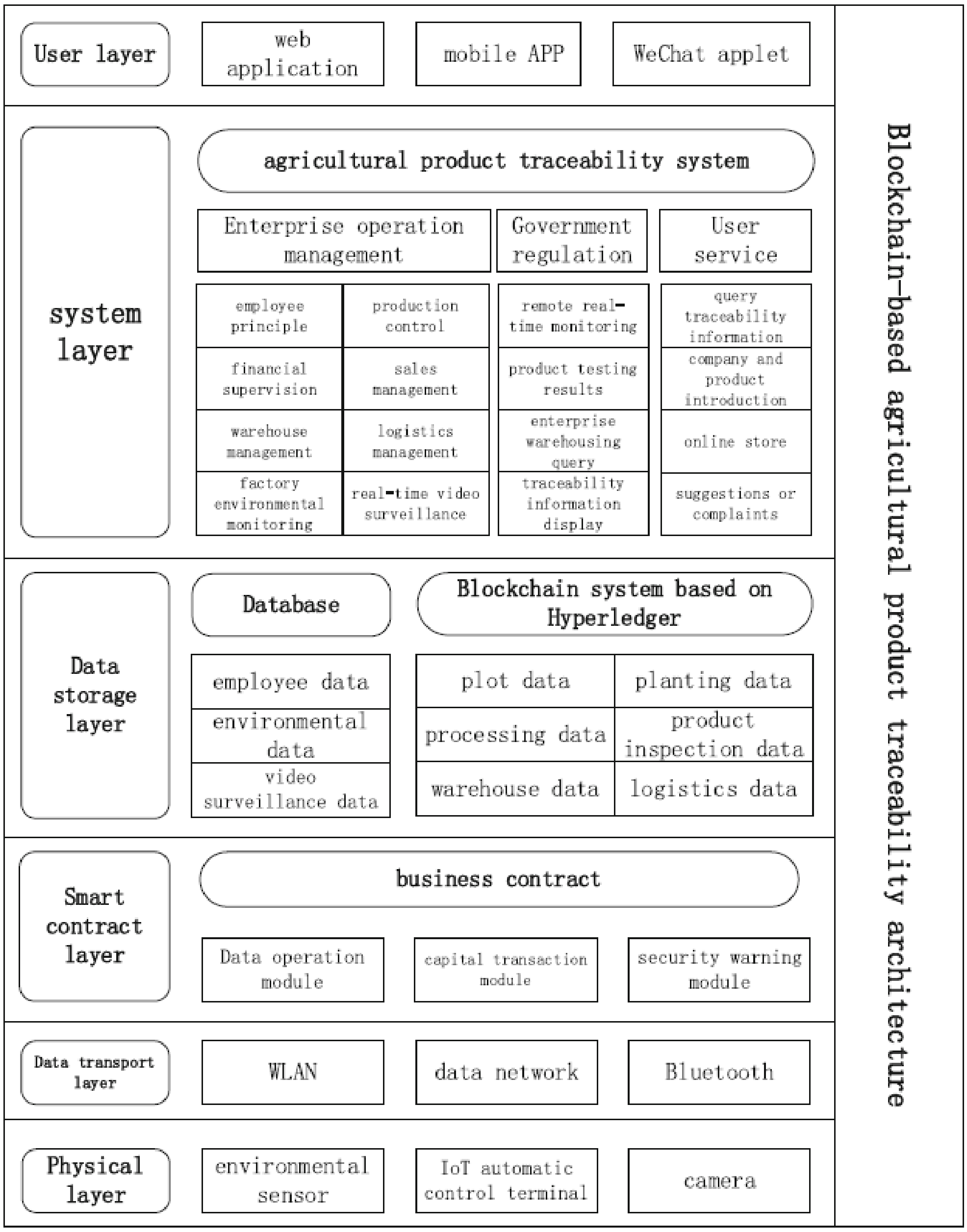

Figure 3 - Architecture of the Blockchain-based Traceability System [76].

The architecture of a blockchain-based traceability system is structured into six distinct layers.

The **User Layer** serves as the interface between the users and the system, including various stakeholders such as farmers, processors, manufacturers, distributors, regulators, and customers. It supports web applications, mobile apps, and WeChat applets, facilitating user interaction with the system. An applet, in this context, refers to a small application designed to perform specific tasks within a larger application environment, like WeChat.

The **System Layer** may include operational management software, government supervision software, or customer service software. Operational management software handles the company's production activities, including employee management, production process control, financial details oversight, storage situation management, and logistics and product transportation consultation. Government supervision software is utilized by governments to oversee company production activities, while customer service software underpins company-customer interactions. The system layer acts as a control component, transforming high-level inputs from the user interface and conveying information between the user and the Data Storage Layer.

The **Data Storage Layer** is crucial for data storage and management. It utilizes both traditional databases and blockchain systems (based on Hyperledger) to store various types of data, including employee data, environmental data, processing data, warehouse data, and logistics data. The blockchain ensures the immutability and security of key traceability information.

The **Smart Contract Layer** is designed based on the commercial agreement between companies. This layer includes a data operation module that facilitates data augmentation and retrieval tasks; a capital transaction module that automates the pre-agreed capital transaction process between companies, such as the automatic payment from buyer to seller upon successful delivery and verification of raw materials; and a security warning module that automatically notifies the system administrator of unauthorized access or data irregularities detected within the blockchain system.

The **Data Transport Layer** is responsible for transmitting data from the physical devices (sensors, cameras, IoT terminals) to higher system layers using WLAN (Wireless Local Area Network), i.e. a data transport technology enabling wireless communication between devices, ensuring connectivity for data transmission, data networks, and Bluetooth technologies.

The **Physical Layer** encompasses the actual hardware, including environmental sensors and IoT control terminals, that collect and transmit data to the blockchain system.

Figure 4 illustrates the functioning model of a blockchain-based traceability system.

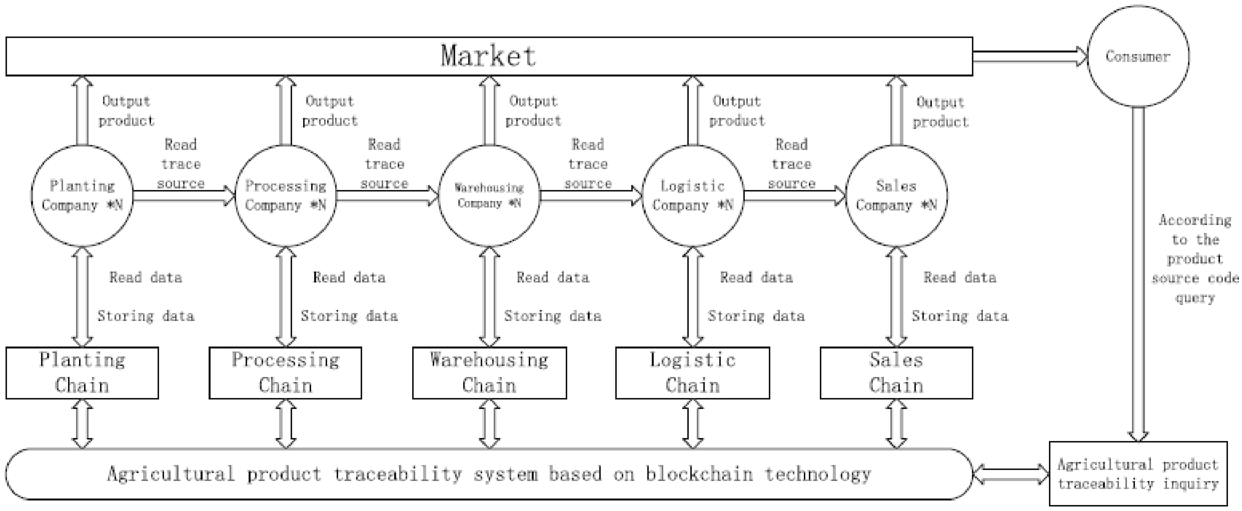

Figure 4 - Operational Model of a Blockchain-based Traceability System [76].

The traceability process in the food chain begins with the grower, responsible for food production. Utilizing blockchain technology, the grower records details about the food products and agricultural conditions, such as soil characteristics, cultivation techniques, and treatments used. Each process stage is stored in distinct blockchain blocks, with timestamps marking the exact time of each event.

As the food moves to the processing company for processing, details of this stage are linked to the grower's block and recorded as data in their ledger. If the processing involves multiple stages, each is meticulously noted in the blockchain. Similarly, each stage receives information from the previous block, with details about the respective stage added.

Ultimately, the finished food product reaches the consumer, who can access complete traceability of the food chain via the blockchain. Thus, the blockchain ensures each step in the food chain is immutable and easily verifiable, enhancing the transparency and safety of the food production system.

CONCLUSIONS

Concluding this analysis on the role of digitalization in the traceability of the food processing industry, it is clear that transparency and accuracy in traceability are indispensable. Blockchain technology, with its decentralized and immutable structure, stands out as a promising solution for ensuring information integrity. However, for traceability to meet market needs effectively, manual data recording and entry into the blockchain, even when supported by specially formulated databases, may lead to errors and fail to guarantee the veracity of shared information. Thus, integrating

Industry/Quality 4.0 tools with Blockchain Technology for automatic data recording emerges as a valuable approach.

Traceability accuracy can be quantified by metrics such as data entry accuracy, data consistency, retrieval speed, and error rate. These metrics measure how reliably and precisely a system tracks the production, processing, and distribution stages of a product. For instance, accuracy can be assessed by comparing blockchain records against a known benchmark and calculating the percentage of correct entries.

Digitalizing processes presents significant investment and implementation challenges, particularly in less industrialized countries. The agri-food sector's operators may lack necessary training and show resistance to adopting innovative systems. Yet, successful case studies, such as the Placido Volpone Winery's blockchain implementation, demonstrate that innovation is feasible with tailor-made solutions, even though many are still in the pilot phase.

At this development stage, blockchain's impact on agri-food supply chain management does not lead to decentralization but strengthens existing networks. Typically, a central company takes on supply chain management responsibility, encouraging suppliers to join a blockchain-equipped supply chain network.

The future lies in the digitalization of all processes, but universal solutions are needed. Considering suppliers serving multiple processing companies, adapting to different traceability systems complicates achieving a standardized approach. For food supply chain traceability to become a shared benefit reality, technology usage must become universal. Humidity, location, pressure sensors, labeling, and reading systems should enable standardized, shared, and synchronized information flows, ensuring universal access across the supply chain following the same traceability standards.

The Baseline project [77] by Microsoft Dynamics 365 exemplifies a potential future challenge. It aims to integrate informational systems across sectors, creating a shared and certified data ecosystem, allowing different systems to "communicate" and synchronize, sharing real-time data of any nature, such as quality data along the entire production chain. Baseline [77] is a standard enabling state machines to achieve and maintain data consistency and workflow continuity, using a network as a common frame of reference. A toolkit helps companies coordinate complex and multilateral business processes and workflows while ensuring privacy and keeping data in record systems. This suggests a significant step toward solving the challenge of interoperability between different blockchain and digital traceability systems. Developing common standards and communication protocols is crucial for effective data sharing and consistency across the supply chain, facilitating collaboration among sector actors.

In summary, addressing the current gaps in the food processing industry to enhance traceability requires a strategy based on the complete digitalization of processes through the implementation of Industry 4.0/Quality 4.0 tools, ensuring data authenticity. To assure information immutability and transparency, decentralized systems like blockchain technology are the most reliable solutions in terms of security and privacy protection. Moreover, secure data synchronization and sharing through system interoperability would be a fundamental added value for an efficient traceability system.

This study, through a literature review combined with real-case studies analysis, has shown that blockchain-based approaches significantly enhance supply chain transparency and quality management in the food processing industry. While highlighting the potential and challenges of practical implementations, it underscores the crucial need for modern digital tools to meet societal demands for food safety and quality, particularly emphasizing transparency concerning raw materials, processing, and preservation methods. This comprehensive overview of modern digital tools' role in improving quality traceability in the food processing sector is not only original but offers valuable insights for businesses aiming to adopt these technologies for better quality management and traceability.

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Author contributions

All authors contributed to the study conception and design. Literature search and data analysis were performed by Elisa Verna; Gianfranco Genta and Maurizio Galetto critically revised the work. The first draft of the manuscript was written by Elisa Verna and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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77. Baseline protocol (2022) Amster Based 2022 - Baseline Protocol@EthDevConnect