Digital Traceability of Quality in the Food Processing Industry

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STRUCTURED ABSTRACT

Purpose - This study examines the enhancement of quality traceability in the food processing industry through modern digital tools such as, for example, the integration of blockchain technology. A literature review is combined with real-case studies analysis to explore this evolving field.

Design/methodology/approach - Adopting a mixed-method approach, the research first conducts a thorough literature review to understand current digital trends in the food processing industry. Then, it analyzes some real-case studies to assess the practical application of these technologies for quality traceability.

Findings - The study demonstrates that the approaches based on blockchain technologies significantly enhance supply chain transparency and quality management in the food processing industry. It highlights both the potential benefits and the concerns faced in practical implementations.

Research limitations/implications – This study is constrained by the current lack of cultural orientation in the food processing industry for an in-depth examination of modern digital tools and their practical application. The utilization of such tools is mainly limited to a few isolated case studies, rather than being explored through a structured and widespread experimental campaign.

Practical implications: The findings provide practical guidelines for businesses in the food processing sector looking to implement modern digital tools for improved quality traceability and management.

Social implications: This study highlights the critical role of modern digital tools in meeting societal demands for food safety and quality in the food processing industry, particularly emphasizing the importance of transparency in information related to raw materials, processing, and preservation methods.

Originality/value: Starting from literature review and case studies analysis, this paper provides a first comprehensive overview of the use of modern digital tools to enhance quality traceability in the food processing sector.

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

Paper type: Research paper.

INTRODUCTION

In the global food industry, traceability is crucial for ensuring food safety and quality, driven by the need for transparency following various food scandals. Traceability, defined as tracking an entity's history, application, or location through recorded identifications, meets consumer demands for safety and transparency while boosting business competitiveness and optimizing production processes (Corallo *et al.*, 2018).

In the European market, traceability is either mandatory or voluntary. Mandatory traceability, aimed at financial transactions, often lacks detailed quality information, while voluntary traceability allows for more comprehensive data collection (Demestichas *et al.*, 2020). The European Union (EU) reinforced traceability through Regulation (EC) No 178/2002, which established core food law principles and procedures, including the European Food Safety Authority (EFSA), to trace food, feed, animals, or substances through all production stages (European Parliament and of the Council, 2002). Technological innovations like the Internet of Things (IoT), Radio Frequency Identification (RFID), and blockchain have significantly advanced traceability systems, enhancing data management efficiency, accuracy, and reliability (European Commission, 2024).

The IoT has revolutionized data collection in the agri-food sector by using devices and sensors for continuous monitoring. RFID assigns unique identifiers for seamless tracking, and additional technologies like Wireless Sensor Networks (WSN), Near Field Communication (NFC), Datamatrix, and QR Codes further improve traceability by efficiently storing and providing detailed product information.

Despite improvements, IoT-based systems relying on centralized server-client models face vulnerabilities, such as data integrity and security risks, due to dependency on a single entity for data management (Feng *et al.*, 2020). The agri-food supply chain (AFSC) faces challenges including product theft, adulteration, and non-compliant labeling, demanding comprehensive solutions for transparency and reliability.

Developing a universal traceability system is challenged by standardization issues, as proprietary solutions lead to compatibility problems and higher costs. Efforts towards global harmonization have been made with standards like the European Article Numbering Uniform Code Council (EAN/UCC) (GS1) (European Commission, 2024). Blockchain technology offers a decentralized, secure ledger that enhances supply chain transparency, mitigates trust issues, and improves data integrity, supporting a comprehensive history of food products from origin to distribution (Feng *et al.*, 2020).

Blockchain, combined with IoT devices, promises end-to-end tracking of food products. Pilot projects indicate a trend towards more efficient and flexible traceability systems. Successful blockchain applications in the food sector require collaboration between multidisciplinary experts, including agri-food specialists and IT professionals, to address supply chain complexities effectively, as noted by Reddy et al. (2023).

In this framework, 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.

Further, 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. Incorporating empirical case studies and tools like Business Process Modeling (BPM) and Unified Modeling Language (UML) diagrams, this research contributes to advancing the discussion on food supply chain management. It aims to pave the way for a universal traceability system that meets the varied needs of different food supply chains, marking a step toward enhanced quality assurance and transparency in the industry.

The rest of the paper is structured as follows. The “Background” section provides an overview of the agri-food industry and the role of digital tools in traceability. The "Methodology" section presents the mixed-method approach, including literature review and case study analysis. 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. In section “Designing a Traceability System for the food processing industry”, a model for an effective traceability system using digital tools is proposed. Finally, the “Conclusions” section summarizes the study and suggests directions for future research.

BACKGROUND

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, involving all agents or actors and operations that contribute to the product's formation or transfer to its final use (Malassis and Padilla, 1986). The Food Value Chain (FVC) represents the complete process through which food is produced, processed, distributed, and made available to consumers, characterized by complexity and fragmentation (Nguyen and Do, 2018). Key features include:

- Short Life Cycle: Food products necessitate rapid processing and reduced storage times.
- Perishable Goods: Require specific transport and storage conditions.
- Agile Production Cycles: Adapt to frequent setup cycles due to product seasonality.
- Product Diversification: Numerous varieties and options within the chain.
- Rigorous Quality Controls: Strict adherence to national and international regulations.

Given its peculiarities, FVC management requires active cooperation and coordination among diverse actors to benefit all participants and satisfy consumer needs. Key actors include:

- Agricultural Producers: Growers, ranchers, and fishermen producing raw materials like fruits, vegetables, meat, fish, and dairy.

- Agricultural Input Suppliers: Companies providing fertilizers, pesticides, farming equipment, seeds, and other agricultural resources.
- Processors: Transform raw materials into packaged food products. Primary processing includes cleaning, peeling, grading, and packaging, while secondary processing turns ingredients into consumable foods.
- Distributors and Wholesalers: Purchase and distribute large quantities of food products to retail stores, restaurants, and other destinations.
- Restaurants and Retailers: Places where consumers purchase food, including restaurants, supermarkets, markets, and specialty stores.
- Transporters and Logistics: Handle the transportation of food products, ensuring safe and timely delivery to retail points.
- Food Safety and Regulatory Authorities: Government agencies ensuring food safety and compliance with health regulations.
- Consumers: Their choices influence food product demand and purchasing behaviors.
- Non-Governmental Organizations (NGOs): Address issues related to sustainable agriculture, food security, and combating food waste.
- Financial Service Providers: Offer lending and investment services to support food production and distribution.

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

Blockchain technology, introduced by Satoshi Nakamoto in 2008, enables secure, transparent digital transactions through a decentralized ledger (Nakamoto, 2008). It records transactions in cryptographically linked blocks, ensuring immutability and data integrity through peer-to-peer (P2P) networks (Lee, 2015). Blockchain's evolution can be 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 can be categorized into several types, each with unique characteristics and suited for specific use cases:

- Public Blockchain: Open and accessible to anyone, public blockchains are secured through decentralized consensus mechanisms and offer transparency and security without requiring trust among users. Examples include Bitcoin and Ethereum.
- Private Blockchain: Controlled by a centralized entity or a limited group of participants, private blockchains regulate access and participation, offering faster transaction validation due to simpler consensus mechanisms.
- Consortium Blockchain: Governance is distributed among participating companies in a consortium, with access regulated by a select group sharing common interests. This type combines elements of decentralization with controlled access.
- Hybrid Blockchain: Combines features of both public and private blockchains, allowing for managed access and privacy while maintaining some decentralization.

Selecting the appropriate blockchain type is crucial for project success and optimizing supply chain management (Kramer *et al.*, 2021).

Conceptualized by Nick Szabo in the 1990s, smart contracts automate and enforce contract terms through code, activated by predefined conditions without intermediaries (Mohanta *et al.*, 2018; Szabo, 1996). These contracts, ranging from deterministic to non-deterministic, improve traceability and efficiency but require interdisciplinary expertise to address challenges (Bosona and Gebresenbet, 2023; Christidis and Devetsikiotis, 2016).

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. The methodology consists of two primary components: a thorough literature review and a case study analysis.

Literature Review

The literature review provides a comprehensive understanding of current digital trends and technologies in the food processing industry, including IoT, RFID, and blockchain. It synthesizes findings from scientific articles, conference papers, book chapters, and reviews, highlighting the strengths, weaknesses, and gaps in existing research, forming a foundation for the case study analysis.

Case Study Analysis

The case study analysis 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.

Detailed information about each case study was collected from multiple sources, including company reports, academic articles, industry publications, and interviews. A key contributor was an anonymous expert currently serving as a Tech Strategist at Microsoft, who previously held the position of Global Blockchain Traceability Product Strategy Lead and Innovation Manager at Ernst & Young (EY) and was directly involved with several blockchain projects, including those at Placido Volpone, Bofrost Italia, and Spinosa (see "Business Case Studies" section). This expert's testimony and access to internal documents provided invaluable insights. The collected data was systematically analyzed to identify common patterns, challenges, and successes in blockchain implementation. Key metrics included supply chain transparency, quality management improvements, and noted efficiencies or cost reductions. The analysis traced the evolution of blockchain from simple data notarization to more complex and verifiable traceability solutions involving multiple stakeholders.

Designing a Traceability System

In light of the insights gained from the literature review and case study analysis, the development of a standard reference model to address the complexities of the supply chain is proposed. It involves a detailed analysis of actors, processes, resources, and data flows to ensure seamless traceability. The approach utilizes Business Process Modeling (BPM) and Unified Modeling Language (UML) to create a comprehensive framework that integrates blockchain technology, enhancing data integrity and transparency across the food value chain.

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 Agri-Food Supply Chain (AFSC) exploring Internet of Things (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.

Year	Documents
2023	216
2022	209
2021	131
2020	88
2019	56
2018	20
2017	3
2016	2

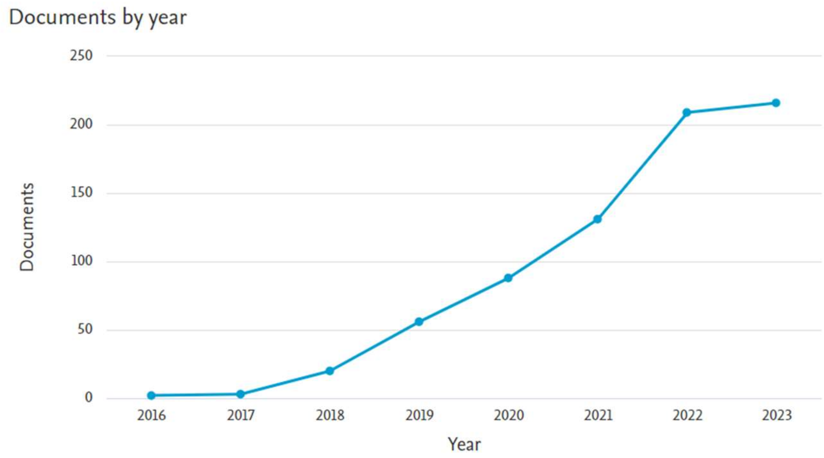

Figure 1 – Annual Count of Blockchain-Related Publications in Agri-Food Traceability (2016-2023). Source: Scopus.

Reviewed Articles and Key Insights

Yang et al. (2021) propose a blockchain-based system for the traceability of fruits and vegetables, integrating blockchain and databases to ensure data immutability and efficient queries. Keerthivasan et al. (2022) explore blockchain technology in the fruit and vegetable supply chain, noting adoption challenges like expert opinions, strategies, and administrative structures.

Tian (2016) analyzes blockchain and RFID technologies for fresh produce and meats, highlighting significant advantages and challenges compared to centralized solutions. Building on this, Tian (2017) incorporates IoT tools and HACCP analysis to enhance the decentralized approach. Xu et al. (2021), and Morais et al. (2023a) propose a blockchain-based traceability system for urban fruits, aiming to mitigate quality and fraud risks with IoT 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. (2019). This approach aims to prevent blockchain overload by utilizing associative storage space. Instead, Tse et al. (2017) 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.

Kaijun et al. (2018) propose a dual-chain solution for the agricultural supply chain, improving transparency, confidentiality, and system efficiency. Caro et al. (2018) introduce AgriBlockIoT, a blockchain platform integrating IoT sensors with Ethereum or Hyperledger.

Koirala et al. (2019), Baralla et al. (2019), Lin et al. (2019), and Yang et al. (2021) advocate for a similar framework using consortium blockchains and smart contracts. Specifically, Baralla et al. (2019) and Yang et al. (2021) promote an on-chain/off-chain approach to manage data confidentiality.

The "BRUSCHETTA" project (Arena *et al.*, 2019) uses blockchain to trace and certify the Extra Virgin Olive Oil supply chain, leveraging IoT technologies. Following this, Fernandes et al. (2022) propose a similar application using smart contracts and Web DApps. Carrefour UAE's collaboration with IBM Food Trust was presented at the 2022 Arab International Conference on Information Technology (Eletter *et al.*, 2022).

Among the most recent documents reviewed, Gazzola et al. (2023a) analyze Lavazza's pilot project, which recently introduced a blockchain-tracked product on the market with the xFarm platform, showcasing the evolving landscape of blockchain application in food processing traceability.

Challenges and Advantages in the Application of Blockchain Technology

Selecting the appropriate blockchain type, such as "blockchain and database" (Yang *et al.*, 2021), Ethereum or Hyperledger applications (Caro *et al.*, 2018), dual-chain solutions (Kaijun *et al.*, 2018), or Blockchain for IoT (Arena *et al.*, 2019; Morais *et al.*, 2023a; Xu *et al.*, 2021), depends on the application domain's specific characteristics. This choice requires a detailed pre-evaluation of qualitative and technical aspects, drawing insights from literature.

Transitioning to blockchain in the food processing industry presents several challenges. Resistance to adoption is significant due to the disruption of established practices and stakeholder pushback. The digital transformation introduces complexity, involving numerous actors and layered responsibilities, complicating technological change management. Forming robust agreements on data storage and sharing is critical to safeguard sensitive company information, especially in the global agri-food context. Implementing blockchain traceability systems is financially and resource-intensive, requiring substantial investment in digital infrastructure and staff training. The digital divide between industrialized and developing nations raises concerns about the technology's cost-effectiveness and accessibility.

Conversely, blockchain technology offers numerous advantages for the agri-food supply chain. Its decentralized nature eliminates reliance on central servers, mitigating food security risks and fostering collaboration. Blockchain enhances security, efficiency, and fraud prevention, vital for maintaining food quality and ensuring consumer safety. The technology's ability to promptly detect system failures can significantly reduce food waste and losses, enhancing supply chain sustainability. Developing common standards and protocols is crucial for effective data sharing and collaboration among various blockchain and digital traceability systems.

Cybersecurity remains a critical issue. Blockchain's encryption and decentralization offer intrinsic security measures, but protecting sensitive information and preventing cyber-attacks require additional safeguards. Blockchain's transparency can engage consumers by allowing them to trace food origin and quality, emphasizing 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 essential for successful implementation.

Looking forward, integrating blockchain with emerging technologies like artificial intelligence (AI) and IoT promises to advance traceability and supply chain management further, enhancing process efficiency and security in the agri-food sector.

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.

The analysis begins with Placido Volpone S.r.l., a winery that has adopted blockchain to notarize data internally, marking a significant step towards greater traceability without external verification. This approach underscores both the progress and challenges associated with the absence of third-party validation, serving as a foundational model in the sector’s move towards transparency.

Progressing further, Spinosa S.p.A. and Bofrost Italia exemplify the next phase of blockchain application, focusing on verifiable and transparent traceability. These cases highlight the enhanced accountability and broader supply chain integration that blockchain facilitates. The quality control manager’s ability to record and make accessible comprehensive quality checks represents a leap towards encompassing external suppliers in the traceability process.

Building upon these cases, Carrefour Italia emerges as a trailblazer in the retail domain, being the first to implement blockchain for the traceability of food products, starting with its own-brand chicken. This initiative reveals the complexity of managing a vast network of suppliers and the resultant improvement in supply chain visibility.

Equally transformative, Lavazza's foray into blockchain showcases the technology’s application in a global supply chain, integrating IoT and Agriculture 4.0 tools for data notarization. This highlights the substantial efforts required to navigate the challenges of international supply chains and less industrialized farming contexts.

Completing the panorama, the TATTOO WINE project by Blockchain Wine Ltd. ventures into new territory by combining traceability with tokenization. This initiative opens up an online marketplace that connects companies and consumers globally, pushing the boundaries of what blockchain can achieve in the food processing industry.

These case studies collectively reflect the sector’s diverse approaches to adopting blockchain technology, from internal data notarization at Placido Volpone S.r.l. to the ambitious global marketplace envisioned by TATTOO WINE. Each story contributes to a richer understanding of blockchain’s potential to enhance brand transparency, foster trust among stakeholders, and improve the overall corporate image, thereby painting a comprehensive picture of the ongoing evolution toward more accountable, transparent, and integrated agri-food supply chains.

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.

The "Wine Blockchain" project at Placido Volpone S.r.l. transitioned through several phases, from a detailed evaluation of winery processes to deploying a blockchain solution that encompassed smart contract creation, data notarization, and launching a consumer-facing landing page, using AgriOpenData—a platform by Ezlab—to simplify data management. This strategic implementation led to a notable 3.5% reduction in production costs and a consequential price increase of 6.2% per bottle, demonstrating a tangible return on investment (ROI) of 14.53%. This initiative, by significantly cutting bureaucratic tasks and boosting product quality control, not only showcases Placido Volpone's innovative approach in the wine industry but also highlights the tangible economic benefits and enhanced market perception achieved through blockchain adoption, thus serving as a compelling model for the broader food processing industry.

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 project, leveraging the Ethereum-based Ops Chain Food Traceability platform, enables manual data entry at various production stages, offering an unparalleled transparency level. It covers breeding and milk collection details, processing at the facility, quality assurance measures, and distribution specifics, ensuring each process step is certified and notarized on the blockchain. Consumers can validate the authenticity and integrity of this information through the public registry on Polygonscan, enhancing trust and demonstrating Spinosa's commitment to quality and transparency.

Spinosa's approach exemplifies how blockchain technology can revolutionize traditional industries by providing end-to-end traceability and setting a new standard in the dairy sector. This case underscores the successful application of blockchain to improve brand reputation, consumer trust, and competitiveness, marking a significant advancement in the dairy industry's embrace of digital innovation.

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 records essential details such as fishing practices, including MSC certification for sustainable fishing, and freezing processes ensuring fish are frozen promptly at the right temperature. It also tracks packaging, storage conditions, and quality control measures, down to the delivery phase, where transportation temperatures are meticulously monitored. This comprehensive transparency extends to making chemical and microbiological control reports publicly accessible, enhancing consumer trust, and demonstrating Bofrost's commitment to quality and safety.

Bofrost's initiative represents a significant advancement in the food industry, illustrating how blockchain can serve as a tool for ensuring food safety and strengthening supply chain 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 set a precedent as the first major retailer in Italy to implement blockchain for food traceability, starting with its outdoor-raised, antibiotic-free chicken production chain in September 2018. This initiative now encompasses an expansive network including 29 farms, feed production sites, and a slaughtering plant. With plans to extend blockchain traceability to its own-brand citrus products, Carrefour's adoption of EY OpsChain Traceability underscores a significant leap towards comprehensive digital transparency. Consumers can access detailed product information - from farming practices and feed to slaughtering locations and transportation methods - simply by scanning a QR code. This approach has not only enhanced Carrefour's supply chain visibility but also significantly boosted sales and customer engagement, reflecting a growing consumer demand for quality assurance.

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 (Beverfood.com, 2022; Gazzola *et al.*, 2023b). 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.

TATTOO Wine: Digitizing the Wine Market

Blockchain Wine Ltd., through its collaboration with EY OpsChain, has developed the TATTOO Wine marketplace to promote and sell premium wines globally, with a keen focus on rapidly growing Asian markets. This e-commerce platform leverages blockchain for wine traceability and tokenization, enabling consumers to purchase wines as digital tokens that represent ownership of uniquely identified wine batches registered on the Ethereum blockchain. This innovative approach to wine sales and supply chain transparency allows real-time tracking of shipments and customs processes, offering a secure and digitized solution for verifying supply chain data and automating procurement and inventory orders. The inclusion of NFC seals in rare wine bottles adds an additional layer of protection against counterfeiting, illustrating the project's comprehensive strategy to enhance product authenticity and consumer trust through blockchain technology.

DESIGNING A TRACEABILITY SYSTEM FOR THE FOOD PROCESSING INDUSTRY

The goal of designing a traceability system for the food processing industry is to establish a standard reference model addressing supply chain complexities. This requires a detailed analysis of actors, processes, resources, and data flows to ensure seamless traceability. A unified approach is proposed to overcome communication barriers between developers and users, utilizing interviews and collaborations to identify system requirements. This leads to a methodological framework using a formalized language for clear business management support, setting the stage for blockchain system design and its translation into executable code.

The methodology emphasizes the importance of Business Process Modeling (BPM) for understanding and supporting information systems (de Oca *et al.*, 2015). It involves a "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 (Corallo *et al.*, 2018).

Business process modeling, used for business process improvement (BPI) and reengineering (BPR) (Anand *et al.*, 2013), represents organizational processes and their interactions. Tools like ADONIS, ARIS, and MS Visio aid in developing models to meet specific requirements, thereby enhancing business process management (Teixeira *et al.*, 2018).

Simplifying the Traceability System Design

This section proposes a model for agri-food traceability, offering guidelines for certification stages, production process mapping, and blockchain data integration. Addressing the diversity in organizational structures, it is crucial to understand each entity for precise planning and outcomes, requiring collaboration between technology and agri-food experts.

The approach can be based on integrated ARIS architecture principles, creating a business process model that simplifies complexities into manageable views.

To tackle the model's intricacy, it can be initially segmented into single views - Organizational, Functional, Product, Data, and Process - as shown in ARIS House (Grigoroudis and Doumpos, 2021) (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 that support business functions in "Application System Type Diagrams," which are key for tracking blockchain data 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, which is crucial for process modeling accuracy. The Data View focuses on structuring and utilizing information within the organization, using Entity-Relationship Models (ERMs) to map key data elements and their interrelations, which is pivotal for establishing a blockchain-based traceability system. Meanwhile, the Product View illustrates the flow from raw materials to finished goods, marking stages where traceability data should be captured for inclusion in the blockchain ledger. Finally, the Process View uses Business Process Modeling and Notation (BPMN) for a detailed representation of organizational operations, informing smart contract design for the blockchain system. This is complemented by Function Allocation Diagrams (FADs), which detail resource allocation and responsibilities within process stages, enhancing the understanding of blockchain's potential for transparency and verifiability.

Through this framework, businesses can develop an effective, blockchain-based traceability system by aligning technological requirements with business processes, ensuring extensive traceability within the food processing industry. This approach simplifies complex processes and underlines the necessity of a unified method for integrating blockchain technology effectively.

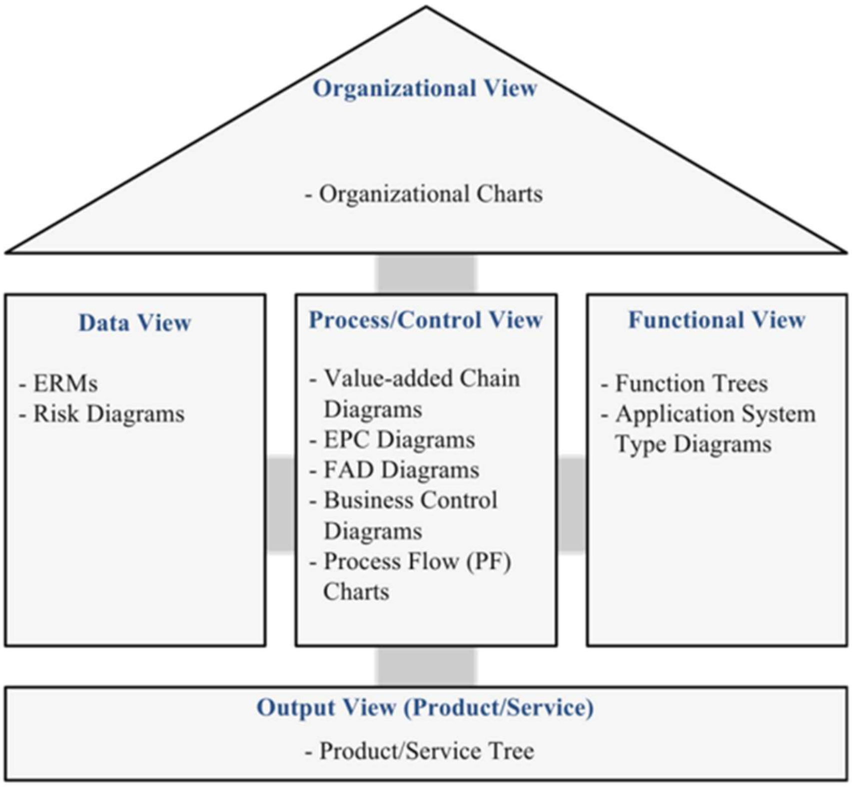

Figure 2 - The Different Views of "ARIS House" (Grigoroudis and Doumpos, 2021).

UML Diagram for Enhanced Traceability

Building on the foundations laid in the previous section, the integration of the aforementioned views culminates in the creation of a unified architecture for process chains (Figure 3). Analyzing multiple entities within the Food Value Chain (FVC) offers a holistic perspective on process integration, essential for strategic coherence and establishing traceability systems (Ciborra, 1997). The UML domain model framework presented by Morais et al. (2023b) details potential blockchain data and interrelations for traceability.

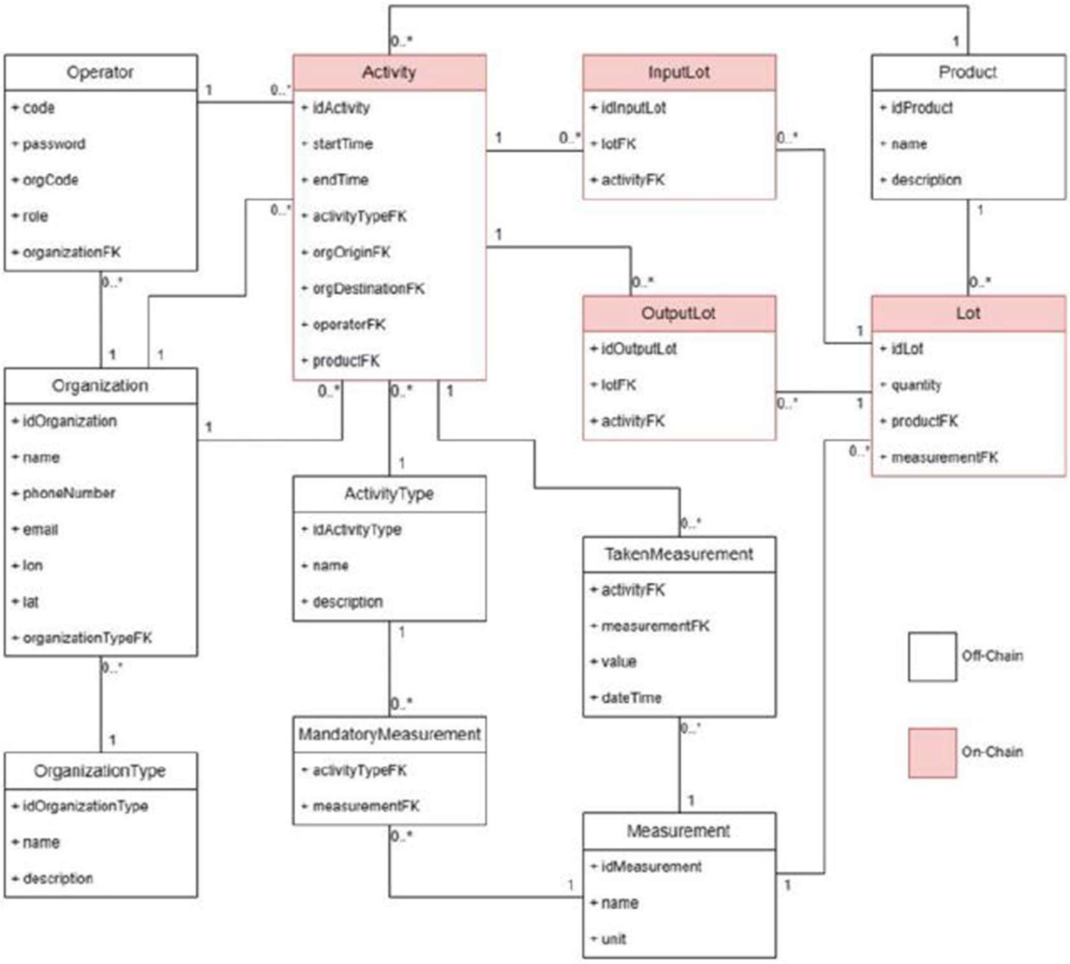

Figure 3 - UML Diagram for Traceability (Morais *et al.*, 2023b).

Implementing a "blockchain + database" methodology allows for the differentiation between data stored on-chain for transparency and off-chain for privacy, represented through distinct color coding (white and pink). The model categorizes eleven distinct classes, essential for the system:

- **Organization, Organization Type, and Operator**: Defines entities engaging in various activities within the chain, each with unique identifiers and roles, ensuring clear delineation of responsibilities and specialization areas.
- **Product and Lot**: Tracks products and lots, distinguishing between database-stored data and blockchain traceability data.

- **Activity Type, Measurement, Mandatory Measurement, and Taken Measurement**: Links activities and required measurements, recording specific data like temperature or pH for accurate and verifiable data capture.
- **Input Lot and Output Lot**: Illustrates dependencies on input and output lots, tracking these elements through the blockchain to maintain a comprehensive view of the product lifecycle.

This structured approach not only simplifies the incorporation of blockchain technology into the traceability system but also enhances the system's integrity and usability across the FVC, ensuring data privacy where needed and transparent traceability where possible.

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 4.

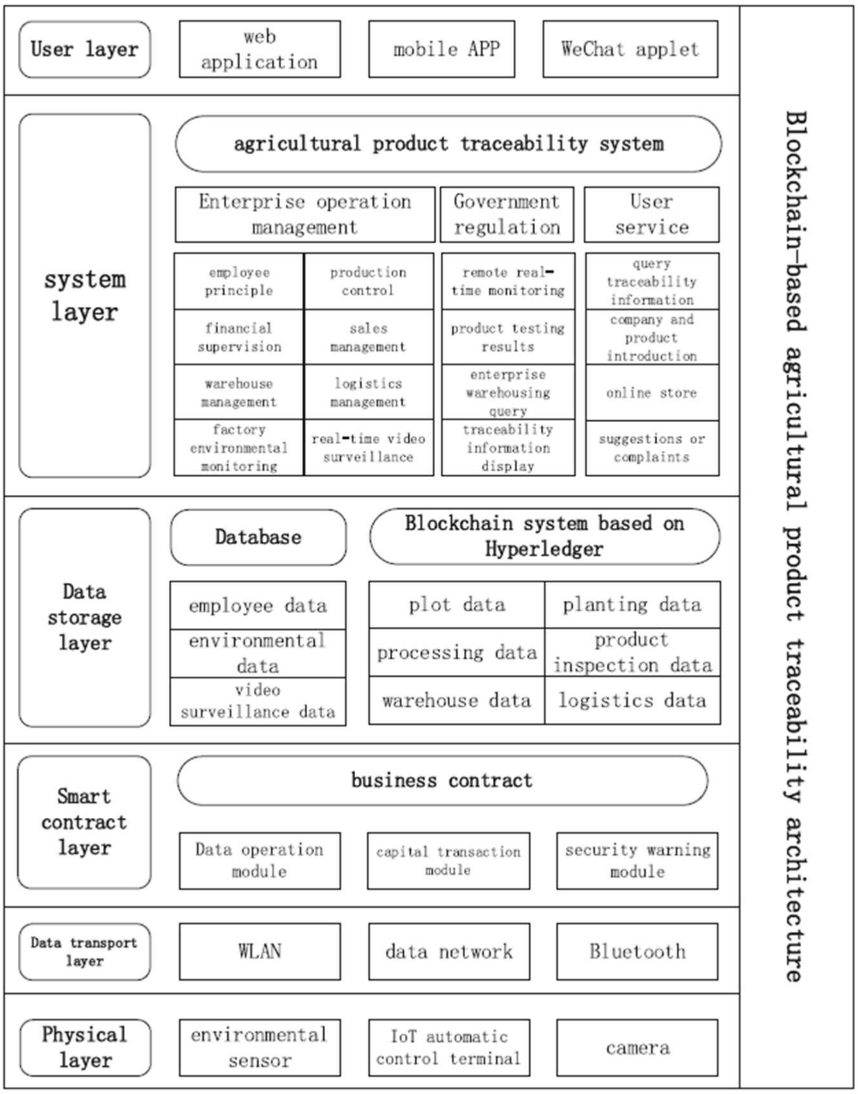

Figure 4 - Architecture of the Blockchain-based Traceability System (Wang and Liu, 2019).

The architecture of a blockchain-based traceability system is divided into six layers:

- **User Layer**: Interface between users (farmers, processors, manufacturers, distributors, regulators, and customers) and the system, facilitating integration with upper-level software systems.
- **System Layer**: Includes operational management software, government supervision software, and customer service software, acting as a control component for transforming user inputs and conveying information between the user and Data Storage Layer.
- **Data Storage Layer**: Responsible for data storage, with the blockchain as the core component. This layer includes a database for non-essential traceability information to prevent blockchain overload.

- **Smart Contract Layer**: Based on commercial agreements, this layer includes modules for data augmentation and retrieval, automated capital transactions, and security warnings for unauthorized access or data irregularities.
- **Data Transport Layer**: Conveys data from the hardware devices of the Physical Layer to higher levels, ensuring all participants are registered users with correct key pairs for digitally signing transactions.

According to Wang and Liu (2019), the operational model of a blockchain-based traceability system is structured as follows. The traceability process begins with the grower, who records details about food products and agricultural conditions using blockchain technology. Each process stage is stored in distinct blockchain blocks with timestamps. As food moves to processing, details are linked to the grower's block and recorded in the ledger. Each stage receives and adds information from the previous block. The final product reaches the consumer, who can access complete traceability of the food chain via blockchain, ensuring immutability and verifiability, enhancing transparency and safety.

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

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 doesn't 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 (2022) 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 (2022) 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 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, including the pioneering blockchain implementation by Placido Volpone Winery, 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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