XIII. Blockchain Technology Implementation for Traceability in the Food Supply Chain – Case Research

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Food supply chains are evolving into coordinated systems, prompting competition between companies and entire supply networks. In this context, Short Food Supply Chains (SFSCs) have emerged as a response to public concerns about food sourcing and handling. Defined by the EU as systems involving few economic actors committed to local development and close producer-consumer relations, SFSCs present both opportunities and challenges. Among key challenges are identity management, transparency, and security. Blockchain technology, introduced shortly after SFSCs gained attention, offers promising solutions by enhancing traceability and linking product information with physical flows. This chapter explores the role of blockchain in addressing traceability challenges and presents a practical case of its application in SFSCs.

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1 Introduction

The globalisation of markets is leading to an increasing need for food traceability. The ability to track and verify the movement of food products along the supply chain has become essential for ensuring food safety, quality, and transparency. Consumers benefit significantly from this development, as they can access food products from various parts of the world in their local markets (Behnke & Janssen, 2020). The demand for diverse food products, especially fresh produce, has altered traditional food consumption patterns. Nowadays, consumers buy food, particularly fruits and vegetables, regardless of the season, often resulting in increased reliance on imported foodstuffs. As Behnke and Janssen (2020) stated, food supply chains are becoming increasingly global and dependent on a growing number of actors, adding complexity to the distribution and logistical processes.

These shifts in consumer behaviour and global trade have led to an increasing need to exchange high-quality information between all actors along the supply chain. Transparency is paramount in modern supply chains, and businesses are expected to provide accurate data on the sourcing, processing, and distribution of food products. To meet these expectations, stakeholders must have full traceability of each product or ingredient in the final product (Behnke & Janssen, 2020). This capability enhances food safety, minimises the risk of contamination or fraud, and ensures compliance with regulatory requirements. Moreover, the ability to collect and analyse traceability data in real-time provides tangible benefits for all actors in the supply chain, allowing for efficient risk management, product recalls, and improved operational efficiencies. A robust traceability system is essential for providing comprehensive information about a food product's origin, processing, sale, and destination (Bertolini et al., 2006).

Traceability is a highly complex process that requires extensive data collection throughout the supply chain. Historically, this process relied on manual data recording, which was prone to errors, inefficiencies, and limitations in scalability. Manually recorded information was later transferred to computer systems or maintained in paper-based records, making data retrieval and verification cumbersome. This manual approach posed several risks, including inaccurate data entry, incomplete records, and inefficient resource allocation. The rapid advancement of automation, digitalisation, and communication technologies has revolutionised traceability systems in recent decades. The emergence of the Internet of Things (IoT) paradigm has played a crucial role in transforming traceability practices. The rapid growth of IoT, sensor technology, and real-time data analytics has enabled fast and efficient data collection through reliable methods such as product identification, transport and storage tracking, component analysis, and system integration (Demestichas et al., 2020). IoT-based solutions enhance real-time monitoring, enabling stakeholders to track food products at every stage of the supply chain, from production to final consumption.

Additionally, blockchain technology has emerged as a transformative solution for traceability, offering secure, immutable, and decentralised data storage. Blockchain enables all supply chain participants to access a transparent and tamper-proof ledger, reducing the risks of fraud and mislabeling. While blockchain technology presents new opportunities for improving food traceability, it also introduces challenges such as data integration, interoperability, scalability, and regulatory considerations (Demestichas et al., 2020). As digital solutions continue to evolve, the integration of IoT, artificial intelligence, and blockchain is expected to shape the future of traceability in the food industry.

The transformation of food supply chains has extended beyond traceability to include structural changes in agribusiness systems. In general, food supply chains and agribusiness systems are evolving into coordinated food networks, fostering competition between individual companies and entire supply chains and networks. These changes have prompted research into new business models for food markets. In the 1980s, a shift in global business practices encouraged agribusiness companies to prioritise strategic partnerships and collaborative supply chain models (Kähkönen, 2012). This transformation led companies to move beyond individual competition and instead operate as integrated entities within broader supply chain networks. As a result, competition within supply chains has intensified, and businesses increasingly view their ability to integrate into efficient networks as a key performance indicator. This shift has also led to the emergence of new collaborative arrangements among stakeholders, fostering resilience and efficiency in the food supply chain (Thomé et al., 2021).

One significant development in modern food supply chains is the rise of Short Food Supply Chains (SFSCs), which emerged in response to public concerns regarding the sourcing, transportation, and handling of food. The EU Rural Development Regulation (1305/2013) defines short supply chains as networks involving a limited number of economic operators committed to working together to enhance local economic development while simultaneously fostering close geographical and social relationships between food producers, processors, and consumers (Official Journal of the EU, 2013). SFSCs are characterised by direct interactions between producers and consumers, often reducing the need for intermediaries and logistical complexities.

In recent years, the prevalence of short supply chains and local markets has increased significantly across the European Union. This trend has facilitated the sale of locally produced agricultural products in community markets, where producers engage directly with consumers, bypassing conventional intermediaries. As a result, the number of intermediaries involved in SFSCs is minimal, allowing producers to capture a larger share of the economic value generated by their products (Vespia, 2021). In contrast, conventional long supply chains involve multiple intermediaries, often leading to a lack of transparency, price distortions, and reduced bargaining power for small farmers. In long chains, consumers also tend to have limited knowledge about the origin and production methods of their food. Notably, approximately 15% of farmers in the EU sell more than half of their production directly to consumers, reflecting a growing demand for local and traceable food sources. These trends are supported by research highlighting the benefits of SFSCs, including fairer pricing for farmers, consumer access to fresh and seasonal produce, reduced environmental impact, and enhanced social cohesion at the local level (Jarzebowski, 2020).

The environmental benefits of SFSCs are well-documented. Most locally sold products are produced sustainably, with lower reliance on pesticides, synthetic fertilisers, and extensive irrigation. Additionally, the reduced need for extensive packaging, refrigeration, and long-distance transportation decreases energy consumption and overall carbon emissions (European Parliament, 2016). By shortening the supply chain, food producers contribute to sustainability by minimising the environmental footprint associated with food distribution.

Beyond environmental considerations, SFSCs also yield significant social and economic advantages. Consumers increasingly prioritise ethical and sustainable food consumption, placing greater value on direct interactions with food producers. This shift has encouraged the growth of small-scale and organic farming, where producers emphasise quality, transparency, and sustainability. SFSCs foster stronger community ties, reinforcing trust between farmers and consumers. Moreover, research suggests that short supply chains contribute to domestic production growth, increased supply volumes, and greater affordability for consumers (Jarzebowski, 2020).

Despite their numerous advantages, SFSCs are not without challenges. The scalability of local food networks remains a concern, particularly in urbanised areas where demand may surpass local production capacity. Additionally, logistical complexities associated with distribution, storage, and regulatory compliance can pose barriers to widespread SFSC adoption. Nevertheless, policymakers and industry stakeholders recognise the potential of SFSCs to promote sustainability, resilience, and economic inclusivity in food supply chains.

As food supply chains continue to evolve, technological advancements, policy frameworks, and consumer awareness will shape the future of food traceability and distribution models. The integration of digital tools, including blockchain and IoT, offers promising solutions for enhancing transparency and efficiency. Meanwhile, SFSCs will likely continue gaining traction as consumers and producers seek viable alternatives to conventional supply chain models. These transformations underscore the growing importance of research and innovation in food traceability and sustainable supply chain management.

2 Traceability in supply chains

Traceability is defined as the ability to identify the past or current locations of items and ascertain their history (GS1, 2007). In the context of supply chains, traceability refers to the process of identifying and documenting the movement of a product or service from its point of origin through all stages of production, processing, distribution, and delivery to the final customer or user. This process also involves collecting and storing relevant information, including details such as time, location, processes, raw materials used, and the responsible actors in the supply chain.

The ability to trace items throughout a supply chain ensures transparency, product safety, and quality control while enabling a rapid response to potential issues. In cases of foodborne illness outbreaks, contamination, or product defects, a robust traceability system allows stakeholders to swiftly identify the source of the problem and remove affected products from the market (Behnke & Janssen, 2020). Moreover, governments and regulatory bodies worldwide impose stringent compliance requirements on supply chain participants, necessitating robust traceability frameworks to mitigate risks associated with counterfeit goods, fraud, and non-compliance.

2.1 Definitions and key concepts of traceability

A review of the literature reveals various definitions of traceability. Wilson and Clarke (1998) describe traceability as the information required to document a product's history, including its transformation processes from the point of origin to the consumer. In broader supply chain contexts, traceability extends beyond physical goods and encompasses services, data, and information flows, ensuring that all aspects of a product's journey are recorded and verifiable.

Two key terms are commonly associated with traceability within supply chains:

- Tracing: The ability to reconstruct a product's history, including the identification of inputs, production procedures, and processing details. Tamayo et al. (2009) define tracing as the capacity to track raw materials through the distribution chain using product serial numbers or batch identifiers. Manos and Manikas (2010) further elaborate that tracing enables stakeholders to verify product origins, assess production conditions, and ensure compliance with quality standards.
- Tracking: The real-time monitoring of a product's movement across the supply chain. Opara (2003) describes tracking as the capability to oversee past and future events, identify potential locations of products, and monitor key supply chain inputs. Tracking systems leverage barcode scanning, RFID (Radio Frequency Identification), GPS tracking, and blockchain technology to enable seamless product monitoring from manufacturing to final delivery.

Thakur and Donnelly (2011) further differentiate monitoring, which refers specifically to food and animal feed traceability across production, processing, and distribution stages. Monitoring ensures that perishable goods adhere to safety and quality requirements, reducing risks associated with contamination and spoilage.

2.2 The role of traceability in supply chain management

A supply chain is a complex and dynamic system involving the coordination of multiple elements, including products, services, information, financial transactions, and knowledge-sharing networks (Lewis, 2022). In the food supply chain, traceability encompasses various industries such as agriculture, horticulture, fisheries, and aquaculture, which contribute to the sourcing and production of food products. The supply chain consists of three main stages (Hayes, 2023):

1. Primary production – Encompasses the agricultural, horticultural, and aquaculture sectors, where raw food materials are cultivated or harvested.
2. Processing and distribution – Include food processing facilities, packaging, storage, and logistics operations to ensure the safe transportation of food products.
3. Retail and consumption – The final stage is where products reach consumers through supermarkets, restaurants, or direct sales channels.

Each stage in the food supply chain plays a critical role in maintaining food quality, safety, and compliance with regulations. Caro et al. (2018) outline the following key phases in food traceability:

- Production: The starting point where agricultural products are cultivated, livestock is raised, or fish is harvested.
- Quality assurance and regulation: Compliance with food safety standards, appearance specifications, and legal requirements.
- Processing: Convert raw materials into consumable food products, ensuring consistency, hygiene, and regulatory adherence.
- Packaging: Protection and presentation of food products, with labelling that conveys essential details such as origin, nutritional content, and expiration dates.

- Distribution and transportation: A critical step in which food products are shipped to retailers or wholesalers. Cold chain logistics play a crucial role in preserving perishable goods.
- Retail: The stage where food products become available to consumers in markets, supermarkets, or restaurants.
- Consumption: The final step is when consumers purchase and consume food, with traceability information ensuring they can verify product authenticity, quality, and safety.

2.3 The importance of traceability in ensuring food safety and quality

The significance of traceability in supply chains extends beyond compliance and transparency—it serves as a fundamental tool for risk management, fraud prevention, and consumer protection. Bertolini et al. (2006) define a traceability system as "the documented identification of operations leading from the production to the sale of a product." The main benefits of traceability include:

- Enhanced food safety: Enables rapid product recalls in case of contamination.
- Fraud prevention: Protects against counterfeiting and food mislabeling.
- Sustainability: Supports responsible sourcing and minimises environmental impacts.
- Consumer confidence: Ensures that consumers receive accurate, verifiable, and ethical information about their food.

2.4 Blockchain technology and traceability

Recent technological advancements have introduced blockchain technology as a powerful solution for enhancing traceability. Blockchain provides an immutable, decentralised ledger that records every transaction within the supply chain, ensuring data integrity, security, and transparency (Boson & Gebresenbet, 2013). The adoption of blockchain in food traceability presents several advantages:

- Real-time visibility: Stakeholders can access tamper-proof food production and distribution records.
- Decentralized verification: Prevents fraud by ensuring all transactions are recorded in an immutable ledger.

- Automation through smart contracts: Facilitates seamless tracking, reducing paperwork and manual errors.

2.5 Standardization in traceability systems

To achieve global consistency in traceability practices, international standards have been developed:

- ISO 22005:2007 – Traceability in the Feed and Food Chain
  - Establishes a structured framework for tracking food from production to consumption.
  - Ensures compliance with food safety regulations.
  - Encourages the use of barcodes, RFID, and other identification methods.
- GS1 – Global Barcode Standards
- Provides unique identification numbers (e.g., GTIN, EAN/UPC, DataMatrix).
- Enhances supply chain efficiency and accuracy.
- Widely adopted for processed foods, retail products, and logistics tracking.

These standards facilitate seamless data exchange among stakeholders, fostering trust, efficiency, and sustainability in modern supply chains.

2.6 Challenges and future directions in supply chain traceability

Despite its advantages, implementing traceability systems presents several challenges:

- High costs: Small producers may struggle with the financial burden of adopting advanced tracking technologies.
- Data integration: Many supply chains still rely on fragmented legacy systems, making seamless data exchange difficult.
- Regulatory inconsistencies: Varying laws across countries pose compliance challenges for global supply chains.
- Cybersecurity risks: Digital traceability systems are vulnerable to cyber threats and data breaches.

Future research and technological innovations—such as artificial intelligence, IoT sensors, and big data analytics—are expected to enhance traceability capabilities further. Governments and private entities are actively exploring strategies to standardise, regulate, and optimise traceability frameworks, ensuring global supply chains' continued safety, efficiency, and sustainability.

3 Traceability technologies in supply chains

3.1 Understanding the technological background of traceability: blockchain

To fully grasp the potential of blockchain technology in enabling traceability, it is essential to understand blockchain's technological background and evolution. Blockchain technology has gained increasing recognition as a revolutionary tool for ensuring data integrity, transparency, and security across various sectors. Originally developed as the underlying technology behind Bitcoin, blockchain has since evolved beyond cryptocurrency applications and is now widely utilised in supply chain management, finance, healthcare, and government operations (Knut et al., 2017).

The development of blockchain technology can be classified into three distinct generations, each expanding the scope and capabilities of the technology:

- First Generation (Bitcoin Era): The initial blockchain development phase focused on Bitcoin and its use as a decentralised digital currency. Bitcoin's primary function was to provide secure, peer-to-peer transactions without requiring an intermediary like a bank.
- Second Generation (Ethereum and Smart Contracts): Ethereum introduced the concept of smart contracts, allowing automated, self-executing agreements encoded on the blockchain. This advancement expanded blockchain’s application beyond financial transactions and enabled programmable, trustless execution of agreements (Knut et al., 2017).
- Third Generation (Beyond Traditional Blockchain): The latest phase in blockchain evolution incorporates various techniques and protocols, addressing issues such as scalability, interoperability, and energy efficiency. These

improvements allow blockchain to cater to diverse user needs, integrating emerging technologies like artificial intelligence (AI), the Internet of Things (IoT), and decentralised finance (DeFi).

Blockchain's flexibility and security have made it an invaluable tool in the banking, healthcare, agriculture, and logistics industries. In the context of supply chain management, blockchain facilitates seamless product tracking, digital authentication, and fraud prevention (Tayeb et al., 2018). Some of its notable applications include (Kamilaris et al., 2019):

- Verification of Intellectual Property (IP) and Patent Rights
- Managing Health Records and Medical Supply Chains
- E-Governance and Electronic Voting Systems
- Real Estate Transactions and Land Registries
- Authentication and Tracking of Agricultural and Consumer Goods.

Blockchain's impact extends beyond technological innovation, reshaping societal structures, economic models, and business paradigms (Ivanuša-Bezjak, 2018). By decentralising trust and removing intermediaries, blockchain fosters more transparent, efficient, and secure global trade ecosystems.

3.2 Blockchain as a distributed and immutable ledger

At its core, blockchain is a decentralised and immutable ledger that records transactions in a secure and transparent manner (Antonucci et al., 2019). Every transaction is stored chronologically in encrypted data blocks to form an unalterable chain. This public ledger is shared across multiple participants (nodes), ensuring data consistency and security.

Each new transaction added to the blockchain must be verified through a consensus mechanism, which requires the approval of the majority of network participants. Once recorded, the information cannot be altered or removed, ensuring tamper-proof data integrity.

The three key characteristics that make blockchain ideal for traceability include:

1. Reliability: Transactions are verified through cryptographic algorithms, eliminating errors and fraudulent activities.
2. Transparency: All supply chain participants can view real-time transactions, increasing accountability.
3. Immutability: Once data is recorded, it is permanently stored and cannot be manipulated (Gradišnik et al., 2022).

In food supply chains, blockchain does not replace internal information systems but rather enhances existing traceability mechanisms by providing a single source of truth. By integrating blockchain, food producers, distributors, and retailers can track each stage of a product's journey—from farm to fork.

3.3 Blockchain's role in supply chain traceability

Cryptographic signatures and decentralised data storage enable the traceability of products using blockchain. Each transaction in a supply chain—such as production, packaging, transportation, and retail—is recorded as a time-stamped event on the blockchain (Sunny et al., 2020). This process ensures full visibility and traceability of products, helping to:

- Prevent fraud by ensuring accurate documentation of product origin and handling.
- Enhance consumer trust by providing verifiable data on food sourcing and quality.
- Improve recall efficiency in case of contamination or safety concerns.
- Facilitate regulatory compliance by maintaining tamper-proof records.

Blockchain technology ensures that a transaction cannot be modified once it is recorded—only new information can be appended. This guarantees an audit trail for every product in the supply chain.

Blockchain also provides real-time visibility of transactions. Each stakeholder—including farmers, suppliers, manufacturers, logistics providers, and retailers—has equal access to the blockchain, ensuring complete transparency.

Decentralisation and security in supply chains

Unlike centralised databases, blockchain operates as a peer-to-peer network with no single point of failure. Each node in the network (e.g., routers, servers, or computers) stores a complete copy of the blockchain, making the system highly resilient (BUILTIN, 2022).

Smart contracts in blockchain-based supply chains

Smart contracts are self-executing agreements programmed into the blockchain. They automate transactions by defining specific conditions that must be met before execution. In supply chains, smart contracts (Curto & Gaspar, 2021):

- Reduce manual errors by automating data entry and compliance checks.
- Speed up transactions by eliminating paperwork and intermediaries.
- Enhance security through encryption, digital signatures, and audit trail.

Before deployment, smart contracts must be rigorously tested to ensure security, reliability, and full functionality (LinkedIn, 2023).

Integrating blockchain with other traceability technologies

Blockchain alone is not sufficient for comprehensive traceability. Its effectiveness is significantly enhanced when combined with other modern technologies.

Radiofrequency identification (RFID) tags

RFID is a wireless technology that enables real-time product tracking. Compared to QR codes and barcodes, RFID offers (Hoogenraad, 2018):

- Faster scanning without direct line-of-sight.

- Higher efficiency in inventory management.
- Seamless integration with blockchain for automated data logging.

Near-field communication (NFC) for secure data exchange

NFC is an extension of RFID technology, allowing two-way communication between objects. NFC technology supports real-time tracking, making it particularly useful for (Ledbetter, 2023):

- Contactless payments and product authentication.
- Tamper-proof verification of supply chain records.

QR codes and digital tracking

QR codes provide a cost-effective, user-friendly solution for tracking product origin and quality. Combined with blockchain, QR codes (Scantrust, 2023):

- Enhance transparency by allowing consumers to scan and verify product details.
- Support sustainability efforts by promoting ethical sourcing.
- Improve recall accuracy by linking each product to verified supply chain data.

3.5 Challenges and prospects of blockchain in traceability

Despite its advantages, blockchain adoption in supply chain traceability faces several challenges:

- Scalability issues: The increasing volume of data transactions may slow down processing times.
- Regulatory uncertainty: Different countries have varying legal frameworks for blockchain implementation.
- Integration complexity: Businesses must invest in interoperability solutions to connect blockchain with existing ERP systems.
- Cybersecurity risks: Although blockchain itself is secure, external vulnerabilities (e.g., hacking of private keys) must be addressed.

Future Trends are:

- Hybrid blockchain models combining public and private blockchains for scalability.
- AI-driven automation to improve supply chain analytics.
- Wider adoption in sustainable agriculture, pharmaceuticals, and logistics.

Blockchain technology is transforming traceability systems by ensuring secure, transparent, and tamper-proof tracking of products across supply chains. When combined with RFID, NFC, and QR codes, blockchain enhances efficiency, consumer trust, and regulatory compliance. Although challenges remain, the future of blockchain in traceability is promising, with advancements in AI, IoT, and decentralised applications driving further innovation.

4 Traceability in food supply chains

4.1 Introduction to short supply chains

Short supply chains encompass various models designed to streamline food distribution while promoting local production, sustainability, and direct relationships between producers and consumers. The core objective of short food supply chains (SFSCs) is to reduce the number of intermediaries, thus ensuring greater transparency, fairer pricing for producers, and improved product traceability (EUFIC, 2021). Common models of short supply chains include (EUFIC, 2021):

- Direct sales between farmer and consumer: This model includes farm sales, market sales, and home delivery, enabling producers to sell directly to consumers without middlemen.
- Community-Supported Agriculture (CSA): Consumers pre-order and pre-pay for farm produce, securing seasonal, locally grown food while supporting farmers' financial stability.
- Collective sales to institutions: This model focuses on supplying food to schools, hospitals, and public institutions, emphasising local sourcing and sustainability.
- Distance selling: Farmers and producers use digital platforms to sell products directly to consumers, facilitating wider accessibility of local produce.

The establishment of joint sales networks and short supply chains offers an optimal approach to increasing efficiency, improving distribution channels, and ensuring consistent product quality. Stakeholders can leverage collective resources to expand sales networks and enhance supply chain effectiveness by cooperating within existing producer groups. Agricultural cooperatives and regional producer organisations serve as a foundation for developing sustainable short-supply chains that strengthen relationships between farmers, retailers, and public institutions (CZR Murska Sobota, 2018).

4.2 The role of blockchain in food supply chains

Blockchain technology is rapidly gaining prominence in areas beyond cryptocurrencies, particularly in agriculture and food supply chains. The globalisation of food markets has led to increasingly complex supply chains, requiring enhanced transparency, safety, and traceability. In addition, shifting demographics and evolving consumer preferences—such as increased demand for organic, fresh, and minimally processed foods—necessitate more sophisticated traceability solutions.

Consumers today, especially in Europe and North America, are willing to pay a premium for high-quality food products that provide detailed information about their origin, production methods, and safety certifications. This has prompted food industry stakeholders to explore new, innovative traceability technologies, with blockchain emerging as one of the most promising solutions (Tribis et al., 2018).

Blockchain technology was integrated into short supply chains soon after its emergence, offering significant benefits in tracking, data security, and transaction verification. Studies indicate that 40% of companies implementing blockchain technology operate in the agriculture and food production sectors (Vadgama et al., 2021).

4.3 Challenges in traditional short supply chains

Short food supply chains, while beneficial, face significant challenges in identity management, data integrity, and operational efficiency. Many transactions within these supply chains remain manual, involving multiple independent stakeholders who maintain separate databases. This fragmented approach creates bottlenecks, errors, and a lack of transparency, leading to issues such as (Pavlović, 2017):

- Data inconsistencies due to manual record-keeping.
- Limited trust among stakeholders due to a lack of verifiable data.
- Inefficient information sharing, leading to delays and potential fraud.
- Slow transaction processing, increasing operational costs.

Blockchain as a standardised solution for short-supply chains

Replacing fragmented and outdated systems with a standardised blockchain-based solution can significantly enhance the efficiency and reliability of short supply chains. Blockchain technology offers key advantages, including (Lovrec, 2019):

- Management of digital identities for all supply chain participants.
- Real-time tracking of transactions among all stakeholders.
- Verification of product origin, material flows, and financial transactions.
- Creation of an immutable, tamper-proof ledger with verifiable transaction records.
- Reduction in transaction time and overall operational inefficiencies.
- Increased trust among stakeholders by ensuring data integrity and transparency.

Consumer engagement through digital traceability

The digital transformation of short supply chains enables greater consumer involvement. Consumers can now directly interact with farmers and food producers, gaining valuable insights into where and how their food is produced. This fosters increased trust, brand loyalty, and a preference for locally sourced food (Collison et al., 2019).

Blockchain technology plays a pivotal role in enhancing efficiency, transparency, and security in short-food supply chains by:

- Providing real-time verification of product origin and production conditions.

- Ensuring food safety compliance through immutable records.
- Reducing fraud and mislabeling by preventing tampering with product information.
- Enabling rapid product recalls in case of contamination.

4.4 The structure of food supply chains and blockchain integration

The food supply chain consists of three primary layers, each of which plays a critical role in ensuring traceability and data accuracy (Ehsan et al., 2022):

1. Physical Flow (Top Layer)

- Represents the actual movement of food through the supply chain.
- Includes harvesting, processing, packaging, distribution, and retail.

2. Digital Stream (Middle Layer) encompasses digital tracking technologies, such as:

- QR codes for product authentication.
- RFID (Radio Frequency Identification) for inventory tracking.
- NFC (Near Field Communication) for secure product verification.
- Online certification and digital signatures to verify food safety compliance.
- IoT sensors and mobile apps for real-time monitoring of food conditions.

3. Internet and Web Infrastructure (Bottom Layer)

- Serves as the backbone for data sharing and blockchain connectivity.
- Enables cloud-based traceability platforms that store encrypted records accessible to all stakeholders.

Blockchain's Role in Each Layer (Kamilaris et al., 2019):

- Physical Flow: Each product's origin, production conditions, and handling are logged in the blockchain.

- Digital Stream: Technologies such as RFID, QR codes, and NFC tags feed real-time data into the blockchain.
- Internet & Web: Decentralized storage and verification mechanisms ensure permanent, immutable records.

4.5 Future of blockchain in short supply chains

Blockchain integration in short-food supply chains is still evolving, with continuous improvements in efficiency, scalability, and user adoption. Future trends include:

- Artificial Intelligence (AI) and Blockchain Integration
- AI-powered analytics for predicting supply chain disruptions.
- Automated fraud detection and quality assurance systems.
- IoT Sensors for Smart Agriculture
- IoT-enabled devices that monitor soil conditions, temperature, and humidity.
- Real-time updates on harvest schedules and production efficiency.
- Decentralized Finance (DeFi) for Small Farmers
- Blockchain-based microfinance and credit systems for small-scale farmers.
- Improved access to transparent financial transactions.
- Regulatory Standardization and Cross-Border Adoption
- Development of global blockchain standards for interoperability between countries.
- Regulatory compliance frameworks ensuring safe and ethical food production.

Blockchain technology is revolutionising short supply chains by enabling secure, transparent, and verifiable tracking of food products. Blockchain improves efficiency, trust, and compliance across all supply chain stakeholders by integrating digital identity management, smart contracts, and real-time tracking technologies.

While challenges remain, ongoing technological advancements and regulatory developments will further drive the adoption of blockchain in food supply chains, ensuring safer, more sustainable, and consumer-friendly food systems.

5 Implementing a traceability system in a short supply chain – case research

5.1 Introduction to Green Point

Green Point is the largest and most advanced regional short supply chain for food supply in northeastern Slovenia. Established in 2013 by local farmers, Green Point has grown into an extensive network comprising over 100 farmers, food producers, and cooperatives engaged in field, greenhouse, and processed food production. Green Point operates a dedicated logistics centre equipped with storage and refrigeration capacities capable of handling over 80 tons of fresh produce to facilitate efficient logistics.

Green Point is committed to connecting local farmers with end consumers as a distribution hub for short supply chains by promoting high-quality, locally produced, and sustainably sourced food products. The organisation's mission is twofold:

- Ensure consumer safety and satisfaction by providing fresh, traceable food.
- Promote sustainable farming practices and support local economies and communities.

The short supply chain model employed by Green Point significantly reduces the number of intermediaries, thereby ensuring:

- Fairer pricing and improved profitability for farmers.
- Enhanced traceability and food safety for consumers.
- Greater sustainability and reduced environmental impact due to shorter transportation distances.

Through its logistics and distribution network, Green Point supplies fresh fruits, vegetables, and local products to a wide range of public institutions (e.g., schools, kindergartens, elderly care homes) and private institutions (e.g., restaurants, wellness centres, hotels). Additionally, Green Point operates a retail store and an online marketplace, further increasing accessibility to locally sourced, traceable food.

The short supply chain of Green Point consists of several interconnected phases, ensuring the efficient movement of food products from farmers to consumers. Figure 1 includes the main stages (Balaic, 2024):

1. Production: Farmers cultivate crops using sustainable agricultural practices.
2. Harvesting and Collection: Fresh produce is harvested, sorted, and transported to the Green Point distribution centre.
3. Storage and Processing: The produce is stored in cold storage or processed into secondary food products.
4. Logistics and Distribution: The products are prepared for delivery and transported to various public and private institutions, as well as Green Point's retail outlets.
5. Retail and Consumer Access: Products are made available in Green Point stores and online platforms, where consumers can verify their origin and quality.

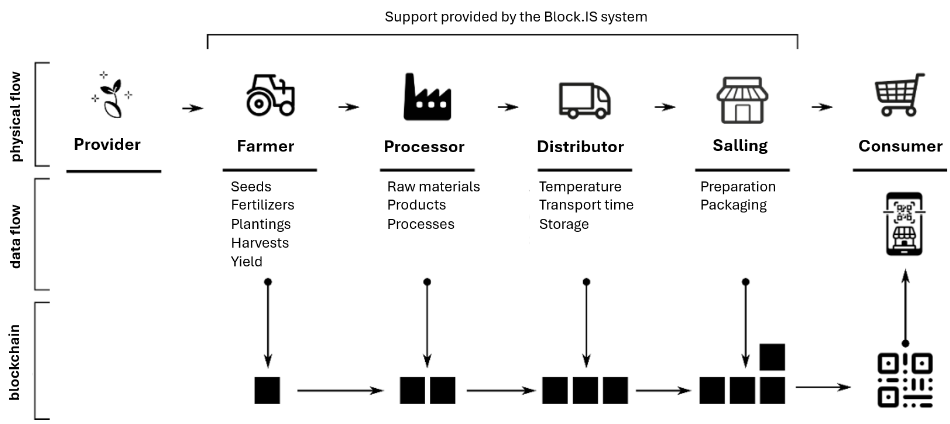

Figure 1: Schematic of the phases and flow of collected data in the short supply chain of the Green Point

Source: (Balaic, 2024)

5.2 The structure and operations of Green Point

The operations of Green Point revolve around several key activities that ensure efficient food production, distribution, and sales while maintaining high traceability standards. The first step in the supply chain is cultivation, where farmers grow more than 20 varieties of vegetables. The outdoor production cycle typically runs from April to October, while greenhouse cultivation extends from February to November, allowing for year-round supply. Most of the vegetables grown by Green Point's farmers are certified under the national quality scheme "integrated production," which emphasises environmentally friendly and sustainable farming methods.

Once the crops are harvested, farmers immediately sort and package the produce before sending it to the Green Point distribution centre. Unlike conventional supply chains, where farmers store large quantities of produce in separate facilities, Green Point centralises storage in its logistics hub. This allows for better quality control and more efficient organisation of inventory. After arriving at the distribution centre, the produce is temporarily stored in cold storage before being prepared for delivery. The logistics team ensures that food products are efficiently transported to customers across the Pomurska region and stocked on the shelves of the Green Point store.

Green Point's retail store plays a crucial role in connecting consumers directly with local food producers. The store is more than just a marketplace—it also serves as an educational hub where consumers can learn about food traceability, sustainable agriculture, and the origins of their food. Green Point enhances trust in locally produced food by promoting consumer awareness and encourages informed purchasing decisions. Additionally, consumers can verify the origin of products using their mobile phones, further reinforcing transparency in the supply chain.

Beyond its commercial activities, Green Point functions as a Living Lab, fostering collaboration among primary producers, food companies, technology providers, consumers, local authorities, and other stakeholders. This multi-partnership approach encourages innovation and the adoption of new technologies that support sustainability, improve efficiency, and strengthen the resilience of local food systems.

5.3 The Role of Blockchain in Green Point's Traceability System

Blockchain technology plays a pivotal role in Green Point's traceability system, ensuring the accurate tracking of food products throughout their lifecycle. In the broader context of food production, reliable traceability is essential for maintaining food safety, quality assurance, and regulatory compliance. Errors, missing information, or inaccessible records can lead to supply chain disruptions, product recalls, and a loss of consumer trust. To address these challenges, digital technologies must be designed to capture and monitor data in real time, providing a verifiable and immutable record of each transaction.

Green Point has adopted blockchain technology to create a unified tracking system for its short supply chain. Blockchain's decentralised nature ensures that all recorded transactions are secure, tamper-proof, and transparent. Unlike conventional databases, where data can be altered or lost, blockchain creates a permanent digital ledger in which transactions are time-stamped and cryptographically signed. Each transaction, whether it involves harvesting, processing, or distribution, is linked to the previous one, forming a continuous chain of verified records. This immutable record-keeping system guarantees that all supply chain participants can access reliable information about food products at any stage of the process.

The use of blockchain in Green Point's traceability system has provided several key benefits. It enables real-time tracking of transactions and material flows, reducing inefficiencies and improving supply chain coordination. Stakeholders can verify the authenticity and movement of food products, which helps prevent fraud and mislabeling. Additionally, blockchain enhances consumer trust by allowing individuals to access product information through QR codes, ensuring greater transparency regarding food origins, quality certifications, and sustainable practices.

5.4 Stakeholders and their roles in the traceability model

Green Point's traceability system relies on a well-defined network of stakeholders, each playing a crucial role in ensuring the safe and efficient passage of food through the supply chain. The key participants include producers, processors, transporters, retailers, and consumers.

The traceability model of Green Point's short supply chain relies on blockchain technology to enhance transparency and security. Each stakeholder in the supply chain has a unique digital identity recorded on the blockchain. The roles of key stakeholders are as follows (Figure 2):

- Producers (Farmers): Responsible for cultivating and harvesting fresh produce.
- Processors: Convert raw agricultural products into processed goods such as juices, pasta, and oils.
- Transporters: Ensure the timely and safe delivery of food products to distribution centres and retailers.
- Retailers: Provide a direct link between the supply chain and consumers, ensuring that products are traceable and meet quality standards.
- Consumers: Can verify product authenticity using QR codes or mobile applications, ensuring transparency and trust.

Figure 2: Illustration of the solution design of the blockchain-based traceability model in the short supply chain Green Dot

Source: (Balaic, 2024)

Blockchain technology records every transaction in real-time, enabling all participants to track the movement of food products through the supply chain. This system reduces fraud, prevents mislabeling, and increases trust between producers and consumers.

Unlike traditional supply chains, Green Point has omitted the role of providers who supply raw materials, such as seeds and fertilisers. The organisation has created a more streamlined supply chain with fewer intermediaries, ensuring that food moves more efficiently from farms to consumers.

Technical implementation of blockchain in Green Point's traceability system
Green Point has implemented a private blockchain network based on the Hyperledger Besu framework to avoid high transaction costs associated with public blockchain networks. This enterprise-friendly blockchain solution ensures that only verified participants have permission to access and record transactions, improving security and scalability.

The blockchain node network used in Green Point's traceability system ensures data security, transparency, and decentralisation. Each node in the network plays a specific role in verifying, storing, and distributing traceability information.

The node network structure includes three main components (Figure 3):

1. Proxies: Manage data exchange between different nodes and enable communication across the blockchain network.
2. Validators: Verify transaction validity and maintain the integrity of recorded data.
3. Peers: Provide read access to blockchain records, ensuring that all stakeholders can access real-time product traceability data.

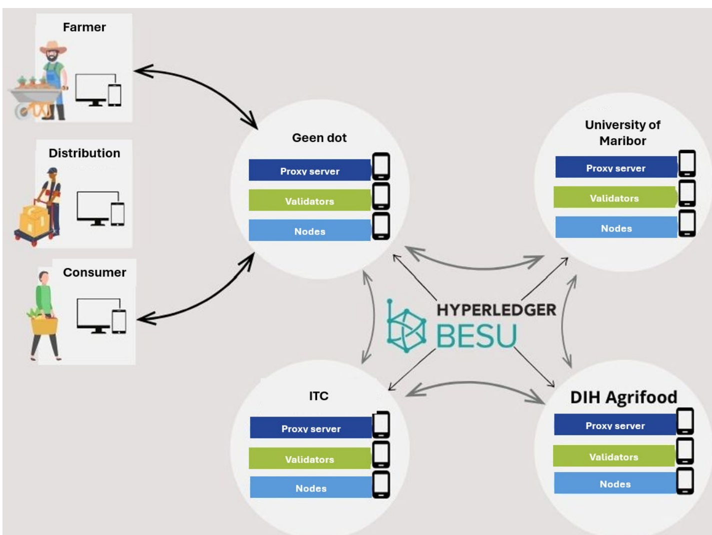

Figure 3: Node network
Source: (Balaic, 2024)

The implementation of a private blockchain network (Hyperledger Besu) allows Green Point to avoid high transaction costs associated with public blockchains. Additionally, the InterPlanetary File System (IPFS) is used for decentralised data storage, ensuring that large files such as images, digital signatures, and certifications are securely stored. At the same time, only references are recorded on the blockchain.

Green Point has integrated the InterPlanetary File System (IPFS), a decentralised file storage network, to optimise data storage and retrieval. Large files, such as images, certifications, and transaction records, are stored off-chain on IPFS, while blockchain stores digital proofs and metadata that point to the original documents. This hybrid approach ensures efficient use of blockchain storage while maintaining data integrity and accessibility.

Green Point's traceability solution is accessible through a mobile application, allowing stakeholders to record relevant data at each stage of the food chain. Farmers, processors, and retailers input production, processing, and logistics information, creating a comprehensive digital record of every product's journey. Consumers can then access this information by scanning QR codes on product packaging, providing full transparency and reinforcing trust in local food production.

Green Point's implementation of blockchain-based traceability represents a significant step toward ensuring transparency, efficiency, and trust in short food supply chains. Green Point has enhanced traceability, food safety, and consumer confidence by leveraging decentralised digital records, real-time tracking, and cryptographic security. The integration of blockchain technology not only optimises supply chain operations but also supports sustainable agriculture and local economic development.

Looking ahead, further advancements in artificial intelligence, IoT, and smart contracts could further enhance blockchain's role in traceability and supply chain optimisation. As Green Point continues to innovate, its model serves as a blueprint for other short supply chains seeking to implement reliable, transparent, and scalable traceability solutions.

6 Conclusion

In recent years, consumer concerns regarding food's origin, safety, and quality have grown significantly. This heightened awareness has increased consumers' willingness to pay a premium for food products that provide proven traceability and transparent information about their origin. Despite advancements in traceability technologies, most existing systems remain centralised and outdated, particularly in terms of data exchange, interoperability, and security. These shortcomings highlight the urgent need for modern digital traceability solutions that leverage information and communication technology (ICT), radio frequency identification (RFID), the Internet of Things (IoT), and blockchain to enhance transparency and trust in food supply chains (Demestichas et al., 2020).

Among the various technological solutions available, distributed ledger technology (DLT), such as blockchain, offers significant potential to address many of the existing challenges in food traceability. By ensuring immutability, decentralisation, and transparency, blockchain enhances trust between stakeholders, prevents fraud, and enables real-time monitoring of food products throughout the supply chain. However, implementing blockchain-based traceability systems presents new challenges for organisations, including technical complexity, cost of adoption, and integration with existing supply chain management systems. Overcoming these challenges requires strategic planning, technical expertise, and collaboration among industry stakeholders.

The growing popularity of short supply chains and local food markets across the European Union reflects a broader shift toward sustainable, transparent, and ethically sourced food production. Unlike conventional long supply chains, where farmers have limited bargaining power, and consumers lack insight into food origins, short supply chains enable direct transactions between producers and consumers, often involving only one intermediary or none (Vespia, 2021). Research has shown that approximately 15% of farmers in the EU sell more than half of their produce directly to consumers, reflecting an increasing demand for alternative, locally sourced food options (Jarzebowski, 2020). The advantages of short supply chains include fairer prices for farmers, improved consumer access to fresh and seasonal produce, a reduced environmental footprint, and stronger social cohesion at the local level.

From an environmental perspective, short supply chains contribute to more sustainable food production by reducing the need for extensive transportation, packaging, and energy consumption. Locally sourced food is typically grown using fewer pesticides, synthetic fertilisers, and water resources, further minimising its ecological impact (European Parliament, 2016). The emphasis on direct transactions between producers and consumers also fosters stronger community ties and trust, reinforcing the importance of ethical and sustainable food systems (EIP-AGRI, 2019).

Despite the potential of blockchain and other digital traceability technologies, their widespread adoption remains hindered by several challenges. Many stakeholders in the food supply chain lack the technical expertise to implement and maintain blockchain-based traceability systems effectively. Additionally, disagreements on standardisation, interoperability, and governance structures have further slowed adoption. For blockchain technology to reach its full potential in food traceability, organisations must develop user-friendly solutions that simplify system integration and enhance accessibility for all stakeholders, from small-scale farmers to large retailers.

The implementation of blockchain-based traceability at Green Point serves as an example of both the opportunities and challenges associated with adopting new technologies in short-supply chains. While blockchain technology provided an effective solution for ensuring food traceability, improving supply chain efficiency, and enhancing consumer trust, the transition required significant effort in training employees and adapting business processes. Employees initially faced difficulties in embracing the new system, as they had to move away from traditional record-keeping methods and adapt to digital solutions. The digitisation process was not immediate, requiring all stakeholders to fully integrate and fully accept the new blockchain-enabled business model.

The successful implementation of blockchain-based traceability in short food supply chains depends on several factors. First, continued investment in digital literacy and employee training is essential to ensure the adoption and utilisation of new technologies effectively. Second, collaborations between food producers, technology providers, and regulatory bodies are necessary to establish standardised traceability frameworks that promote interoperability and compliance with food safety regulations. Lastly, integrating emerging technologies such as AI-powered analytics, IoT-enabled monitoring, and decentralised finance (DeFi) could further optimise supply chain transparency, efficiency, and resilience.

In conclusion, the future of traceability in short-supply chains lies in leveraging advanced digital technologies to create efficient, transparent, and sustainable food ecosystems. Blockchain and other DLT-based traceability solutions hold immense potential in ensuring food safety, fraud prevention, and enhanced consumer trust. However, the road to full adoption requires strategic implementation, overcoming technical barriers, and fostering industry-wide collaboration. As more organisations recognise the value of digital traceability, short-supply chains will continue to evolve, offering greater efficiency, sustainability, and consumer confidence in food production.

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