proceedings

MDPI

Proceeding Paper

Digital Food Supply Chain Traceability Framework †

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† Presented at the International Academic Symposium of Social Science 2022, Kota Bharu, Malaysia, 3 July 2022.

Abstract: The growing importance of digitalising food traceability systems can be attributed to mounting food safety incidents and customer demand for sustainable products. However, most previous studies focused on a specific technology in supply chain management and lacked a holistic approach that could help organisations implement digital food supply chain traceability (DFSCT) systems. This study aims to synthesise the key elements of DFSCT identified in the existing literature and develop a framework to guide future research and practice in DFSCT. The proposed framework captures five dimensions of DFSCT—organisational capacity, enabling technology, the traceability process, expected benefits, and external factors influencing DFSCT system adoption. This study offers important implications for research and practice in DFSCT.

Keywords: digital traceability; food supply chain; food traceability

Citation: Reddy, P.; Kurnia, S.; Tortorella, G.L. Digital Food Supply Chain Traceability Framework. *Proceedings* **2022**, *82*, 9. https://doi.org/10.3390/proceedings2022082009

Academic Editor: Mohamad Rahimi Mohamad Rosman

Published: 7 September 2022

1. Introduction

Foodborne illnesses, food fraud, and food scares are rising with the globalisation of supply chains and market diversification [1]. Food traceability has significant potential to protect consumers as it enables food recall, promotes food quality, safety and defence, and eliminates non-consumable food items. Food supply chain traceability (FSCT) is the ability to keep track of a product's movement and retain its recorded information throughout the supply chain [2,3]. Efficiencies achieved through FSCT help organisations gain competitive advantages in the market as they achieve better product quality, safety, regulation and compliance, sustainable business performance, and operational efficiency [4]. Therefore, academics and practitioners recognise the significance of FSCT and are working to improve the current practice.

Technology is one of the critical drivers that open opportunities for food business operators (FBOs) regarding FSCT [5,6]. Tracing and tracking products in real-time are challenging processes due to their dynamic and complex natures. The digitalisation of traceability eases the process, and enhances supplier communication and decision making. Moreover, advanced technologies hold the potential to change the future of the food industry. Barcodes and RFID are the most used technologies in FSCT [7]. Emerging technologies such as the Internet of Things (IoT), big data analytics, and Blockchain offer innovative and robust solutions to improve food supply chain traceability [6,8]. Finally, the industry will benefit from improved consumer confidence and increased efficiency and innovation [9,10].

The apparent positive impacts of digitalising food traceability are insufficient for its adoption because it lacks a commonly agreed-upon lexicon and implementation guidelines. A comprehensive guide to adopting digital food supply chain traceability (DFSCT) is required. The literature presents extensive studies regarding the traceability process [2,3,11–14] and application of specific technologies such as RFID [15], the IoT [9], or Blockchain [16]. However, few studies acknowledge the importance and role of organisational capabilities such as IT infrastructure [17], IT governance [18], strong leadership [8,19,20], and technical and managerial skills [21]. Moreover, data quality management [12] and DFSCT interoperability [22] are seldom considered. Thus, this study aims to address this gap and accelerate the adoption of DFSCT by proposing a holistic framework of DFSCT to guide future research in DFSCT and facilitate its implementation.

The proposed DFSCT framework was developed through an extensive literature review. First, research papers were selected from the domains of supply chain management, food traceability, food traceability technology, and information systems. Previous studies of the adoption of DFSCT were also explored. Second, papers were thematically analysed to identify key concepts and organise them according to DFSCT dimensions and capabilities. Third, key factors affecting the adoption of digital food traceability were identified to provide a holistic view of DFSCT, its potential impacts, and relationships between key concepts related to DFSCT. The proposed DFSCT framework highlights implications regarding the important fields of DFSCT research and practice.

2. Defining Food Traceability

Academics, supply chain professionals, and regulators have tried to define food traceability but have not reached a consensus. This study follows the definition proposed by Bosona and Gebresenbet [11]:

Food traceability is a type of logistics management that captures, stores, and transmits adequate information about a food, feed, food-producing animal, or substance at all stages in the food supply chain so that a product can be checked for safety and quality control, and traced upward, or tracked downward, at any time required. (p. 35).

Figure 1 presents a schematic representation of this concept. The three components of tracing are backward tracing, forward tracing, and product history information. Backward (upward) traceability facilitates finding the source of a problem by finding its origin and characteristics at every point in the supply chain. In contrast, forward (downward) tracing, or tracking, is the ability to follow a product to gather information at any point in the flow [2]. Both types of traceability are essential for effective FSCT, and companies should aim to perfect each of them. Finally, product history information details the movement, time, inputs identification, and operations that a product experienced in a supply chain [23,24]. Additional notable classifications are internal and external traceability. Internal traceability occurs inside a company or production unit, whereas external traceability tracks physical movement between companies [14,22].

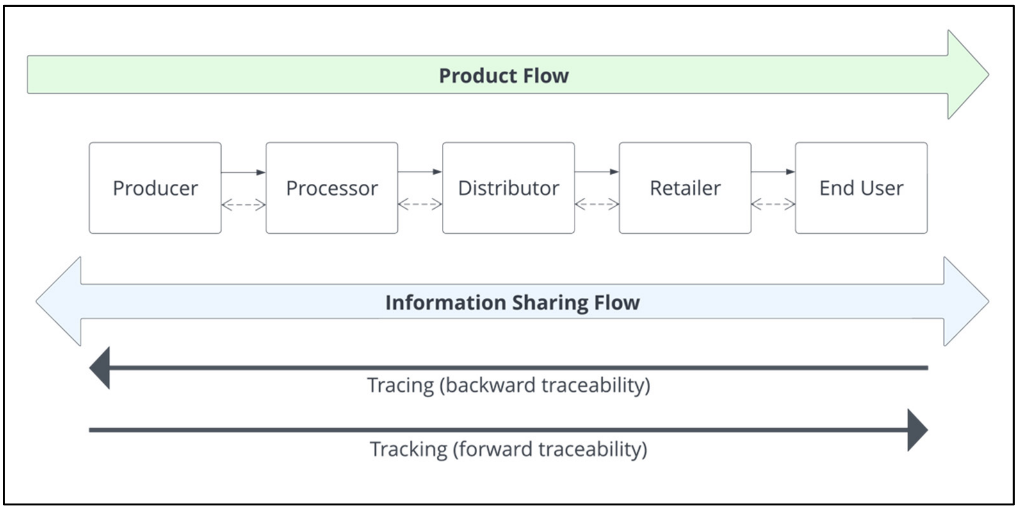

Figure 1. Material and information flow in food supply chain traceability (Adapted with permission from Bosona and Gebresenbet [11], p. 35).

3. Synthesis of Key Concepts

The building blocks of the DFSCT framework, based on our literature analysis and synthesis, are presented below.

3.1. DFSCT Principles

In the literature, traceability principles describe "how" DFSCT is implemented for effective operations. Alternate terminologies found in the literature include components, characteristics, and elements. Various scholars describe DFSCT principles differently across studies, based on their commonalities. In this study, we grouped them into four major principles: (i) identification of traceable resource unit (TRU), (ii) data recording, (iii) data exchange, and (iv) data management. Each principle is briefly described below.

3.1.1. Identification of Traceable Resource Unit (TRU)

TRU is the smallest traceable product or lot [3]; European Council Directive 91/238 defines a lot as "a batch of sales units of foodstuff produced, manufactured or packaged under the same conditions" [25]. In a food crisis, a lot is recalled instead of all affected food instances, allowing targeted operations. Furthermore, TRU simplifies goods semantics, positively impacting the visibility of goods and operational efficiency [22]. Granularity and uniqueness are the two most important factors of TRU identification.

3.1.2. Data Recording

The three types of data recorded are product identification, tracing data, and transformation data, depending on drivers and beneficiaries. The first type is mandatory data for product identification. It includes all information enabling traceability of a specific product [3,25]. The second type is data required to satisfy regulations, standards, or certifications. The third is additional information requested for operational purposes [26]. Captured data are stored in various recording mediums, including simple paper-based systems, computer-based database management systems, Enterprise Resource Planning (ERP), and complex cloud systems [27].

3.1.3. Data Exchange

Data exchange (or integration) enables internal and external traceability by linking, merging, and sharing information [3]. Internal traceability data exchange considers both a product and process data regarding that product moving within the organisation. Data at critical traceability points (CTPs) are mapped using the same TRU identification numbers [13]. A paper-based system is the most widely used for recording data. However, emerging technologies such as RFID, Wireless Sensor Network (WSN), and the Internet of Things (IoT) provide error-free systems and enable explicit linking of necessary data in real-time [28].

3.1.4. Data Management

Information effectiveness, integrity, authenticity, and standardisation are critical to the success of data management [12]. While identification of TRUs, data recording, capturing, and exchange explain the process of traceability, data management focuses on the characteristics of data parsing through the supply chain. It is essential that this information be carefully managed to build and protect trust with supply chain partners and consumers. Therefore, data must be in the correct format, complete, accurate, and credible [29].

Perfecting interoperability, transparency, and accessibility can further improve FSCT. Interoperability allows different technologies to communicate and share information seamlessly [30]. Although this is essential for DFSCT, achieving it could be a challenge, as DFSCT lacks standardisation. Furthermore, transparency between suppliers and customers is vital for adequate informational and knowledge exchange. While visibility poses a risk, the benefits of selective data sharing are worth considering [22]. Finally, confidentiality can be maintained by maintaining different levels of access to data. The control of visibility can build trust [3].

3.2. Technologies

This section provides an overview of the most-used technologies frequently discussed in the literature; their shortcomings and standards are addressed, and followed by an overview of the scope of emerging technologies.

A barcode is a machine-readable pattern of bars and spaces of varying widths. Barcode structure permits accurate, simple, and economical traceability as it is automatic, fast, and precise [15]. GS1 is a common global standard affiliated with Uniform Code Council (UCC) and European Article Numbering (EAN). GS1 Databar and multidimensional barcodes allow barcodes to carry information (including weight, batch numbers, and best-before-dates) in addition to essential identification [10,11]. QR codes are 2D barcodes, which are widely used for automated product tracking and customer reference. However, barcodes require human intervention for positioning and scanning, which introduces errors and inefficiency [3,29].

Radiofrequency Identification is the most widely used food-tracking technology [3,5,31]. RFID tags are electronic labels with a microchip that identifies and tracks tags wirelessly. They help overcome problems associated with traditional solutions (alphanumerical codes and barcode labels) [26,29]. RFID is an effective tool because it supports no-line-of-sight reading. Scanners can read multiple tags simultaneously, have large memories, and allow storage and manipulation of a wide variety of data. Furthermore, automation makes the process of storing and manipulating information in the database error-free and fast [32,33]. The limitations of RFID are high costs and sensitivity towards certain weather conditions and materials [2,3]. The standard for using RFID is EPCglobal Network Standards, launched by GS1, which enables information integration and real-time product visibility in the supply chain. According to the literature, RFID and EPCglobal Network Standards are critical technologies for automating data capture and integrating traceability data [26].

The application of advanced IT in connection to the Internet has become important with regards to information sharing among members of food supply chains [11]. There are two types of traceability information flow models. The first is the 'one step up one step down flow model', where information is filtered at each stage of the supply chain—only certain information is shared with immediate suppliers/customers. The second is the 'aggregated information flow model', where no information filters are applied. Both EU and US regulations have adopted this model for food traceability [2]. Thakur and Donnelly [34] discuss using Electronic Data Interchange (EDI) technology and data format standards, such as Extensible Markup Language (XML), for information exchange in digital traceability systems. EDI enables firms with mature IT capabilities to efficiently exchange standardised and structured data, and XML facilitates the sharing of structured data, mainly via the Internet [3].

Industry 4.0 technologies such as big data analytics, cloud computing, cybersecurity, the Internet of Things (IoT), and Blockchain have the potential to revolutionise food traceability [5]. Research studies regarding these technologies are in nascent stages, but are becoming more frequent in the traceability literature. Alfian et al. [9] used IoT sensors and a machine learning model to improve an RFID-based food traceability system. Lin et al. [35] proposed a framework integrating Blockchain and IoT technologies and demonstrated the capacity of technologies to build a trusted agro-traceability system with all parties in the supply chain, even in the absence of trust between them [36]. However, the high implementation cost, a lack of expertise, and technological immaturity are seen as significant barriers to adopting these modern technologies [5].

3.3. Factors Affecting Adoption of Digital Food Traceability

The literature discusses digital food traceability adoption factors in depth. The following sections elaborate on the benefits and barriers as perceived by FBOs. Drivers are the motivating factors that a company must oblige to successfully establish FSCT systems. Barriers are hurdles that might demotivate an organisation from adopting DFSCT. Table 1 provides an overview of DFSCT key drivers and barriers.

Table 1. Drivers and barriers affecting the adoption of digital food traceability.

Drivers	Barriers
Environment	
• Compliance with regulations, legislation, and certification requirements • Government support and funding • Increase food safety control, reduce food crisis risk, and control disease outbreaks • Mitigate information asymmetry and improve supply chain coordination	• Lack of coordination, trust, confidence, and liability among supply chain partners • Concerns with ethics, privacy, security, reliability, and data protection issues while sharing information
Organisation	
• Decrease the severity, volume, frequency, and cost of a product recall • Improve consumer perception and confidence in brands • Gain competitive advantage, better market access, brand value, and market share • Verify sustainability claims and mitigate potential reputational risk	• Lack of knowledge and awareness • Shortage of skilled staff • Cultural barriers and internal resistance to change • Lack of resources and capital • High initial investment
Technology	
• Availability of digital technologies	• Unreliability of technologies • Lack of interoperability • Lack of uniformity in implementing traceability systems as there are no common standards

4. Proposed Digital Food Supply Chain Traceability Framework

A DFSCT framework (Figure 2) is proposed based on literature analysis and synthesis. This framework captures the critical dimensions of DFSCT, including the required organisational capability, enabling technology, traceability process, and expected benefits. These dimensions are influenced by external factors which either support or hinder the adoption of DFSCT by the food industry. Factors such as access to national IT infrastructure, government provisions, and industry/retailer standards define the operating environment, affecting DFSCT adoption and implementation by FBOs.

DFSCT dimensions have a cause-and-effect relationship in which organisational capability supports the other three dimensions during the development, implementation, and maintenance of DFSCT. Furthermore, technology moderates traceability processes, which results in benefits. Each dimension is further explained regarding specific capabilities in the following subsections.

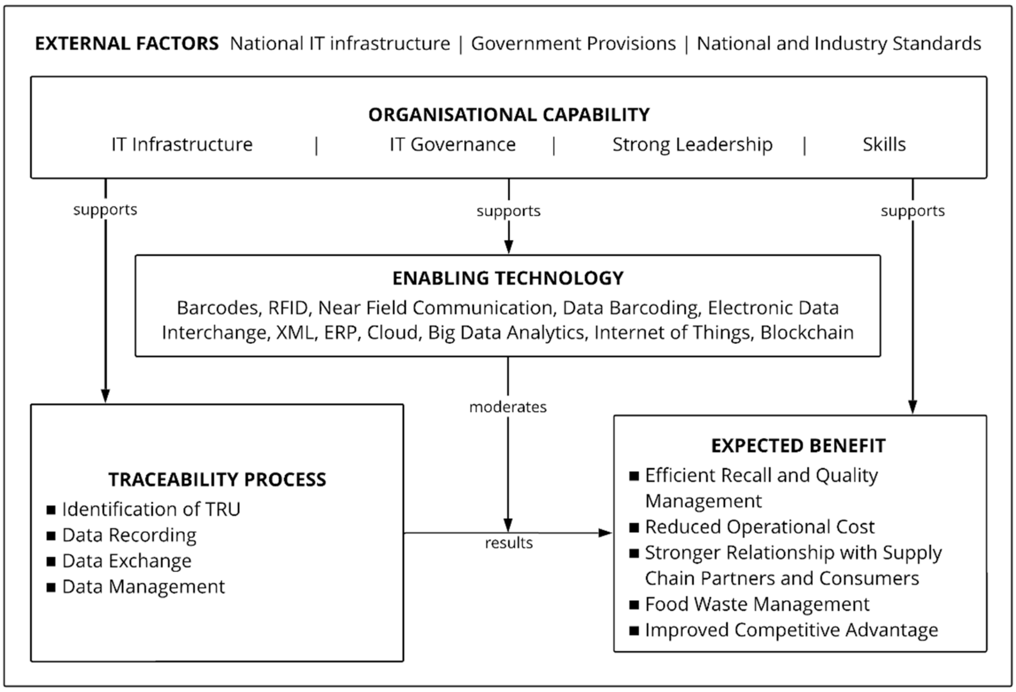

Figure 2. Digital food supply chain traceability framework.

4.1. Organisational Capability

The organisational capability dimension consists of four capabilities that aim to establish the right tools, people, processes, and skillsets. Furthermore, this dimension is the foundation for the success of DFSCT as it supports the other three dimensions. The four capabilities drive efficiency and effectiveness; thus, they are vital for creating a robust and agile DFSCT [37], as explained below.

IT Infrastructure: Appropriate applications, databases, systems, and resources are paramount for the development, implementation, and management of DFSCT; together, these form a technical base for evolving technologies and ongoing management [17].

IT Governance: This capability enables organisations to manage strategic business–IT alignment, IT performance, IT resources, IT risk management, and IT value delivery. IT governance ensures appropriate processes are in place to optimise the application of IT to achieve organisational goals by providing direction to leadership, fostering commitment, and establishing accountability [18].

Strong Leadership: The involvement of upper management is critical to the success of DFSCT. Upper management requires a clear understanding of DFSCT's importance and its adoption [8]. Furthermore, upper management is accountable for engaging with internal and external stakeholders to promote productivity and limit change resistance by improving awareness of DFSCT's functions and importance [20]. Moreover, they must establish organisational policies regarding traceability processes to standardise workflow. Finally, performance measurement is the constant evaluation of traceability processes using metrics. It is a quintessential managerial step for warranting the company's ability to stay on track and use its resources effectively [19].

Skills: This capability focuses on the technical and managerial skills of food organisations' employees [20]. It is an essential dimension because successfully enabling technologies requires new skills. Furthermore, organisations may need to hire new employees or train their existing staff to engage in DFSCT [21].

4.2. Enabling Technology

The eleven most-cited technologies which enable DFSCT included in this dimension are barcodes, RFID, near field communication, data barcoding, electronic data interchange, XML, ERP, cloud, big data analytics, the Internet of Things, and Blockchain. Many other advanced technologies are available for industry-specific applications not mentioned here, such as pH indicators for real-time fish spoilage monitoring. These technologies will optimise traceability processes and improve trust between supply chain partners, leading to better recall efficiencies and cost reductions [3,11].

4.3. Traceability Process

The four capabilities essential for the traceability process are identification of TRU, data recording, data exchange, and data management. The first three capabilities are interlinked. Identification is the first step in the DFSCT process, which enables data recording and data exchange. The data recording capability facilitates recording the product information necessary for traceability. Data exchange facilitates continuous traceability information flow, both internally and externally [2].

The fourth capability, data management, includes all processes associated with managing digital data, including data governance, data quality assurance, master data management, data security management, and data analysis. This capability secures data format, completeness, accuracy, and reliability [12,22], and is vital for establishing standardisation, interoperability, accessibility, transparency, integrity, and authenticity.

4.4. Expected Benefit

This dimension represents the cascading effects of DFSCT gained by a food business organisation. The notable benefits are greater efficiency in recalling products and response to quality management, reduced operational costs, stronger relationships with supply chain partners and consumers, food waste management, and improved competitive advantage. Therefore, along with achieving food safety and quality goals, DFSCT plays a crucial role in providing value, improving responsiveness to customer requirements, and increasing sustainable profit margins [38].

5. Discussion

In this study, a comprehensive DFSCT framework is proposed. The framework extends the existing literature by synthesising and drawing out DFSCT's key elements and capabilities from multiple authors' research [2,3,11,12]. Studies regarding organisational capability [8,17–19], enabling technology [9,15,16], the traceability process [2], and benefits [11,38] were brought together to form one robust DFSCT framework with four dimensions. Thus, an aggregate representation of the managerial, process, and technical aspects of DFSCT was compiled by synthesising the traceability frameworks of numerous authors who explored various DFSCT aspects under different lenses. Future research can focus on selected dimensions of the proposed DFSCT framework.

In terms of implications for practice, this study helps identify essential factors that FBOs should focus on to successfully digitalise their food supply chain operations. First, attention should be given to the proper application and customisation of technology, by prioritising what is best suited for business needs over the latest or trending technology. Second, strong leadership is of utmost importance to ensure the company has the right skills and a smooth digital transition with minimal employee resistance. The human factor can be easily overlooked, but it is one of the most challenging barriers to overcome. Finally, FBOs should establish interoperability by standardising data formats and data exchange methods to improve internal and external information sharing between systems. Consolidated efforts from different departments to improve DFSCT could allow an organisation to leverage it for profits and achieve goals sustainably.

6. Conclusions

The importance of digital food supply chain traceability is increasing because it helps food businesses combat and prevent food fraud, improve consumer safety, and achieve sustainability goals. Furthermore, food organisations can actualise sustainable economic, social, and environmental benefits, consequently building a stronger relationship with their supply chain partners and consumers. However, they cannot adopt DFSCT effectively because traceability practices vary across food sectors and there is no standard DFSCT process. Although researchers and practitioners are giving more attention to digital traceability and supply chain management, there is no mutual agreement or holistic discussion regarding DFSCT. Therefore, this research proposes a DFSCT framework to address this gap.

This study contributes to research and practice. In terms of research, a novel comprehensive DFSCT framework is proposed, which contributes to the literature by introducing a holistic overview of the capabilities that food organisations need to build sophisticated digital supply chain traceability. In term of practice, it provides a practical framework to guide DFSCT implementation. It identifies important factors and organisational capabilities that FBOs' senior management need to manage, develop, and support DFSCT implementation. It also helps senior management understand the expected benefits of DFSCT implementation.

As this study is limited to the discussion in the literature, further theoretical and empirical effort is needed to assess and improve the framework. Future research could enhance the findings by conducting in-depth case analyses of multiple food companies. The engagement of diverse food industries and participants with various backgrounds could further evoke new insights and improve the generalisability of the framework.

Future research to develop a cross-disciplinary multi-level digital food supply chain traceability maturity model using the proposed DFSCT framework as a foundation would be useful for both research and practice. A common DFSCT framework and maturity model could standardise the process of digital food traceability, expediting its implementation. Finally, a user-friendly tool for assessing a company's maturity level and planning its next steps could enhance food product traceability along extended supply chains nationally and globally.

Author Contributions: Conceptualization, P.R., S.K. and G.L.T.; methodology, P.R. and S.K.; validation, S.K. and G.L.T.; formal analysis, P.R.; investigation, P.R.; resources, P.R., S.K. and G.L.T.; data curation, P.R.; writing—original draft preparation, P.R.; writing—review and editing, S.K.; visualization, P.R.; supervision, S.K. and G.L.T.; project administration, S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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