Advances in traceability systems in agri-food supply chains

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Abstract: Failure to deliver safe and high-quality food reduces consumer confidence in the food industry and results in costly food crises, foodborne illnesses and disruption to food supply chains. Recent advances in traceability systems, and associated identification and communication technologies hold the potential to ensure food quality and safety by managing effective traceability throughout the food supply chains. However, deficits in various factors e.g., resources, awareness, training, standards, data management and technology scaling impede exploitation of these cutting-edge traceability technologies. This chapter provides a review of the advances in agri-food traceability systems and technologies, barriers to their implementations, and possible improvement pathways and policy interventions to promote deployment of advanced food traceability systems.

Key words: Food supply chain, Food traceability system, traceability technologies, barriers of implementation, improvement pathways

1. Introduction

Food is a key building block of human physical well-being and consumers' food purchasing behaviour is influenced by three key food characteristics: safety, quality and authenticity (Wilcock *et al.*, 2004; Kendall *et al.*, 2019). However, repetitive occurrence of tragic and costly food crises such as mad cow disease, dioxin contamination, horse meat scandal, *Escherichia coli* (E. coli) outbreaks and *Salmonella* contamination not only diminishes consumers' confidence in food safety, quality and authenticity, but also challenges the underlying credibility of the food industry.

The impact of food incidents is amplified by the globalisation of food trade which causes transnational food safety issues (FAO, 2019). According to the World Health Organisation (WHO, 2015), approximately 600 million cases of global illness and 420,000 deaths are caused annually by foodborne diseases, and this leads to considerable economic burden owing to the associated healthcare use, recalls, disposal, and loss of sales and export. As estimated by the United States Department of Agriculture (USDA), the yearly cost of foodborne illnesses in the United States (US) stands at around $10-83 billion (McLinden *et al.*, 2014), while a single foodborne pathogen, E. coli causes $14.42 million in a year for healthcare use in the United Kingdom (UK) (Naylor *et al.*, 2017). On the other hand, border rejections of export consignments result in significant economic loss, for example, owing to the detection of banned antibiotic and *Salmonella*, seafood supply chains in Asian lower- and middle-income countries are routinely disrupted (Blank, 2018). All these incidents, coupled with a more educated and aware public, underpin increased demand for improved food traceability to communicate the information vis-à-vis food origins, ingredients, processing, quality and safety throughout food supply chains (Rodriguez-Salvador and Dopico, 2020).

Food traceability has been defined by many different organisations, in legislation and scientific articles. The commonly used definition from ISO 22005 (ISO, 2005) referring to traceability as: "the ability to follow the movement of a feed or food through specified stage(s) of production, processing and distribution".

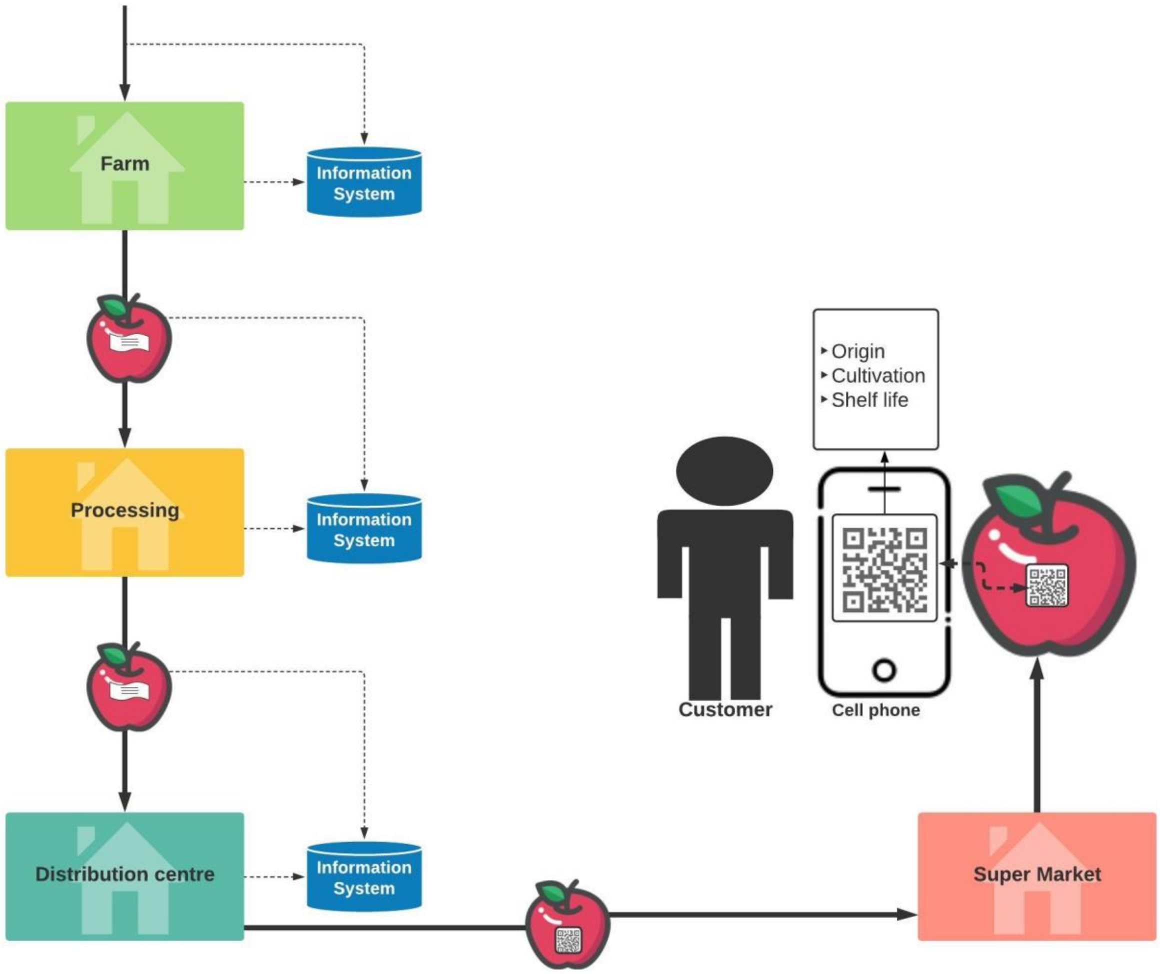

Figure 1.Traceability system in the food supply chain

Implementation of food traceability requires the adoption of a food traceability system (FTS) which is a specific arrangement of processes such as, data capture, data storage and data exchange that is capable of maintaining and communicating the desired product information through all stages of the food supply chain (World Economic Forum, 2019). Food supply chains are becoming increasingly globalised, which poses challenges to guarantee symmetry, trust and transparency for the shared product information. Due to their complex and interconnected nature, global food supply chains face difficulty in seeking to adopt a single, centralised, traceability system architecture especially if this is in the control of a third party, that are monopolistic and opaque in nature. Further, such centralised traceability system architecture is more vulnerable to collapse, since a single point of breakdown can cause the whole system to crash (Tian, 2017; El Maouchi, Ersoy and Erkin, 2018). Distributed traceability system architectures have emerged as a response to these risks, making use of decentralised information capture and storage to deliver improved information symmetry, security, trust and transparency.

Although manual paper-based traceability systems are still commonly used, deployment of computerised FTSs is rising due to the rapid growth of information and communication technologies (ICTs) and the emergence of the Industry 4.0 (the so-called fourth industrial revolution) marked by the automation of production systems. The advancement of FTSs is clearly noticeable in the identification technology practices employed in food supply chains i.e., the extensive use of barcode technologies is being displaced by the use of radio frequency identification (RFID) which provides increased data capacity, reading speeds and accuracy (McCathie and Michael, 2005; Badia-Melis, Mishra and Ruiz-García, 2015). RFID can be supplemented with wireless sensors to support traceability-based product quality monitoring (Thakur and Forås, 2015; Alfian *et al.*, 2020; Islam,Cullen & Manning, 2021). These technologies when integrated with electronic product code information service (EPCIS) data standards, enable efficient product data transfer between supply chain partners (Mainetti *et al.*, 2013) and through to customers. Moreover, Blockchain and smart contract technologies allow increased opportunity for transparency and tamperproof data recording in complex and globally distributed supply chains (Pearson *et al.*, 2019).

Despite the availability of such revolutionary technologies, there are various barriers inherent within food systems which impede successful implementation of FTSs in individual companies or in sub-sections of supply chains (Bosona and Gebresenbet, 2013; Hardt, Flett and Howell, 2017; World Economic Forum, 2019). Barriers to the adoption of FTSs include: a lack of awareness and training on traceability and traceability technologies; a lack of standards development; resource deficiencies, including funding and capacity issues; inefficient data management; and finally, technology scaling issues (Islam and Cullen, 2021). The intensity of these barriers is influenced by the supply chain structure, its relationship dynamics, and the position of companies within the supply chain (Sterling *et al.*, 2015). To harness the transformative power of breakthrough technologies and exploit the potential for FTSs to transform, food supply chains will require clear strategies and pathways to overcome the barriers identified above. This chapter considers exclusively the advancements in agri-food traceability systems and technologies, their implementation barriers and some potential improvement pathways to overcome these.

2. Traceability drivers

Implementation of FTSs is driven by several motivating factors, which are known as controlling forces (Norton *et al.*, 2014) or *traceability drivers* in the literature. Traceability drivers differ across FTSs depending on what type of information the internal or the external stakeholders require. A set of five prominent traceability drivers are adopted from Islam and Cullen (2021) and are discussed below:

2.1 Legislation and certification

Traceability has been embedded as an indispensable requirement in the food legislation of several countries, including EU food law 178/2002; the US Bio-terrorism Act, the US Food Safety Modernization Act (FSMA); and Japan's Food Traceability Act (Bechini, Cimino, Marcelloni & Tomasi, 2008; Charlebois, Sterling, Haratifar, & Naing, 2014; Qian et al., 2020). Many of these food laws require the mandatory recording of the identification of immediate upstream suppliers and downstream customers, in what is known as the "one-up-one down" or "one step forward-one step back" traceability approach.

A key driver motivating many food companies to execute traceability is to meet the necessary legal requirements, so they can stay functional in markets. Some countries agree to abide by traceability regulations to gain access to export markets and introduce their own guidelines. The traceability regulations developed by various parties (e.g., governments, regulators and market actors) are often heavily influenced by the standards developed by the ISO (International Organisation for Standardisation) such as ISO 22005(ISO, 2005) which defines the functional requirements for the implementation of practical FTSs (Islam and Cullen, 2021). The market driver for independently verifiable FTSs has led to the development of third party private certification schemes (Norton *et al.*, 2014).

2.2 Safety and quality

Demonstrating compliance with food safety and quality standards emerges as a strong motivating factor for implementing FTSs, driven by persistent shocks and costly disruptions to food supply chains, including the European horse meat (scandal) substitution for beef, and more recently ethylene oxide recalls across Europe and COVID-19. These incidents impact the perceived trustworthiness of food supply chains and lead to calls for increased transparency surrounding the safety and quality properties of food products (Aung and Chang, 2014). The interaction between traceability and transparency in food supply chains is gaining wider interest (Baralla *et al.*, 2020; Feng *et al.*, 2020) especially where public health has to be ensured within complex food supply chains (Demestichas *et al.*, 2020).

2.3 Customer satisfaction

FTSs both assure and create consumer confidence in the safety and quality of food (*Qian et al.*, 2020; Zhang *et al.*, 2020), especially in a market where consumers have a high level of food safety awareness (Rodriguez-Salvador and Dopico, 2020). Traceability protocols and the designs of FTSs to reduce food safety risks are framed by these consumer preferences (FSA, 2002; Garaus and Treiblmaier, 2021). Indeed, Lam et al., (2020) argue that consumer trust in food safety is based on FTSs and information transparency.

2.4 Sustainability

Traceability has become a strong basis for sustainability related credence claims that are difficult for consumers to ascertain, such as whether a food has been produced through sustainable production practices (Golan *et al.*, 2004). Companies increasingly make use of traceability to validate sustainability claims and gain a competitive advantage from responsible environmental and social practices (Norton *et al.,* 2014; Gallo *et al.*, 2021; Islam and Cullen, 2021). For example, traceability helps companies to authenticate that the good animal welfare practices they claim to adhere to are in place, thereby leading to increased organisational reputation (Golan *et al.*, 2004). With regard to fish supply chains in particular, illegal, unregulated and unreported (IUU) fishing can take place without concern for the environment or strict regulations and fishing quotas. Organisations can make use of FTSs to prevent IUU fish entering fish supply chains (Borit, & Olsen, 2012). The Marine Stewardship Council (MSC) Standard for seafood sustainability requires batch level traceability, confirming that there is no presence of IUU fish from raw produce through to final consumer (Norton *et al.*, 2014; Lin *et al.,* 2020; Islam and Cullen, 2021). Thus, effective FTSs can underpin sustainability claims with regard to a given product.

2.5 Value and efficiency

Inventory management, effective product recall and product distribution are important motivators for companies implementing FTSs (Islam and Cullen, 2021). Retailers make extensive use of traceability for: efficient operational planning (Bourlakis and Bourlakis, 2006; Mishra *et al.,* 2020), resource efficiency (Lin *et al.,* 2020;) optimised shelf-life based distribution planning (Jedermann *et al.*, 2014), prevention of animal theft (Smith *et al.*, 2005) and minimising product recall cost (Opara, 2003).

2.6 Summary

Together, the five drivers identified above—legislation and certification; safety and quality; customer satisfaction; sustainability; value and efficiency—underpin the case for improving traceability in food supply chains and adopting new ICT technologies to deliver more efficient FTSs.

3. Food traceability in theory

Numerous definitions of food traceability exist, provided by various organisations and academics and detailed in multiple pieces of legislation (Islam and Cullen, 2021). The EU General Food Law (2002) defines food traceability as: "the ability to trace and follow a food, feed, food producing animal or substance intended to be, or expected to be incorporated into a food or feed, through all stages of production, processing and distribution". According to the ISO 9000 (2000), "traceability is the ability to trace the history, application or location of that which is under consideration". Olsen and Borit (2013) present traceability as: "the ability to access any or all information relating to that which is under consideration, throughout its entire life cycle, by means of recorded identifications". Islam and Cullen (2021) most recently define food traceability as "an ability to access specific information about a food product that has been captured and integrated with the product's recorded identification throughout the supply chain".

Moe (1998) provides further detail with the description of two main types of traceability in her definition: chain traceability (or external traceability) is the "...ability to track a product batch and its history through the whole, or part, of a production chain from harvest through transport, storage, processing, distribution and sales', whereas internal traceability is the '...ability to trace...in one of the steps in the chain". This means that traceability can operate at two levels simultaneously, the supply chain level and the organisational level; and that for chain traceability to work effectively all discrete internal traceability activities must be operationalised appropriately and synchronised with each other.

Internal traceability is enabled by the recording of product descriptors within the boundaries of a single FBO, while external traceability requires transmission of that information to other links in the chain. Internal traceability is executed by grouping of raw materials and products into batches or lots and assigning them discrete identifiers (Olsen and Borit, 2018; Islam and Cullen, 2021). The batches or lots, alternatively known as traceable resource units (TRU) (Moe, 1998), undergo several transformations that may encompass aggregation (e.g., mixing and combining) or disaggregation (e.g., splitting and portioning), for example, harvested fruit from multiple growers being pooled as one TRU, or conversely a livestock carcass being disaggregated to multiple cuts of meat being distinct TRU. As a TRU move internally within an FBO and/or through the food supply chain, the associated information needs to be communicated in tandem. In essence, information flows through the FTS from material origin to final product enabling traceability and visibility in supply chains. Thus, traceability as described here associates a product and its component parts; the organisations through which the product and its component parts have been transferred; the modifications/transformations that have occurred at each point; and the characteristics of the data itself that in turn give information about the product and any aligned services.

4. Food traceability system (FTS)

The implementation of traceability in food supply chains, in practice, requires discrete FTSs. An FTS is the totality of data and operations that is capable of maintaining desired information about the food product and its ingredients through all or part of the supply chain (World Economic Forum, 2019). Although paper based manual recording is able to execute traceability in a one-up-one-down manner, it does not provide adequate transparency across the FSC. Transparency is defined as "the practice of being open and honest with customers in terms of food sourcing, ingredient lists, nutrition facts, allergen concerns, and ecological impact" (Food Standards Agency, 2017). Lack of transparency results in a greater risk of food adulteration, counterfeiting and mislabelling (Manning, 2019a). Therefore, computerised traceability systems including pedigree, centralised and decentralised data management approaches have emerged which possess the potential to strengthen traceability leading to better transparency across food supply chains. The evolution of traceability systems, from manual to computerised systems and across centralised and distributed systems, is discussed below:

4.1 Manual and computerised traceability systems

Traceability systems have evolved from simple manual paper-based recordings to latest industry 4.0 technology-based information systems. Paper-based databases (Zhang *et al.*, 2010) represent the simplest technique for data recording using paper trails, including the use of product registration books, faxes, paper forms, and postal letters. Paper based manual systems are adequate for implementing one-up-one-down based traceability systems i.e., to record the identification of immediate supplier and customer, and pedigree-based information system, such as the audit trail recording of a product's transformation and ownership as it passes along the supply chain (Alfian *et al.*, 2017; Olsen, 2017). Paper-based traceability systems, involving manual transcription, require less expertise and less infrastructural cost to implement, however they are time consuming, less reliable, less suitable for further analysis and highly prone to human error or data loss (Frederiksen and Bremner, 2001).

Due to the weaknesses identified in paper-based traceability systems, computerised traceability systems, offering improved accuracy and reliability, have been extensively adopted across various food supply chains (Regattieri, Gamberi and Manzini, 2007; Zhang *et al.*, 2010; Feng *et al.*, 2013). Computerised databases can be updated by a manual transcription or an automated transcription through various technologies, for example, barcodes, RFID and

Wireless Sensor Networks (WSN). Computerised traceability systems for chain traceability across food supply chains can be implemented through database software with electronic data interchange (EDI) capacity, centralised cloud-based information systems or decentralised Blockchain technology. Although they require increased infrastructural costs, training and expertise, computerised traceability systems provide improved information storage and retrieval, reliability, transparency, data standardization, security, and ease of subsequent analysis and interrogation.

4.2 Central and distributed traceability system

Traceability systems can be categorised by the degree of independence of the databases used throughout the supply chain i.e., whether the traceability system is based on centralised or distributed information systems (Hugoson, 2007; Tian, 2017). An important distinction between centralised and decentralised information systems is the data location used in individual FBOs for recording and transmitting traceability data, which can be described as totally distributed, compressed and distributed, or centralised (Gandino *et al.*, 2009). In the *totally distributed* approach, data are stored directly as detail such as written words or RFID labels directly on the product or packaging, for example, the use of ear tags attached to the animals containing detailed animal history when the animal is moved from one food supply chain link to the next (Feng *et al.*, 2013). In the *compressed and distributed* approach data are stored in a compressed form (e.g., short code) which is linked to a reference database, for example, a barcode, containing product identification, links a product to a reference database which detail product operation information (McCathie and Michael, 2005). However, all traceability data can also be stored in a centralised database and its link can be attached to the given item, say, in the form of a QR code. Such information system is commonly used in retail store product tagging where the tag code links back to a centralised database containing detailed product information (Tarjan *et al.*, 2014).

Another distinction between centralisation and decentralisation is observed through the choice to store data in a centralised or decentralised information system that influences the way traceability data is integrated or shared across multiple FBOs. In the centralised architecture, a central database owned by an external third party is responsible for all traceability data (Bechini *et al.*, 2005). This architecture requires the responsible FBO to provide to a third party the information related to that activity (Huang, Zhou and Liu, 2019). This information must allow the central database to, at a minimum, record the lot transformation, i.e., the association between the input lot(s) and the output lot(s) (Bechini *et al.*, 2005). This approach, is however, susceptible to single node (central database) attack and data tampering with the loss of data confidentiality leading to decreased data security (Huang, Zhou and Liu, 2019).

In the decentralised approach, the FBO responsible for an activity records the transformation relationships between the associated input and output lots. The FBO then communicates the global identifier of their produced lot through a preferred communication channel (e.g., EDI, product tag or accompanied documents) to the distributor, which, then provides to associate the input with the global identifier of the subsequent output (Bechini *et al.*, 2005). This approach may suffer from lack of standardisation, information tampering and non-transparency (Tian, 2017).

Therefore, increased attention has recently been focused on an alternative decentralised data recording approach known as Blockchain: a chronological chain of blocks with each block added to the chain after storing information regarding a distinct network activity (e.g., transaction, supply chain operation) with an identifiable timestamp (Tian, 2017). All users, considered as nodes in the network, are, with suitable permissions, able to see the recorded data in the chain of blocks at any time, but no one can change it, due to cryptographic protection (Salah *et al.*, 2019). Being an immutable history of network activities, Blockchain provides means to share traceability data among all nodes (i.e., supply chain actors) in the system. Using a Blockchain-based information system removes the risk of using a centralised third-party traceability database, while providing transparency, authenticity, security and tamper proofing of the shared traceability information for all nodes in the system. More detail about Blockchain technology is provided in the next section.

5. Traceability technologies

The so-called fourth Industrial Revolution (or Industry 4.0) is characterised by the ongoing automation of traditional manufacturing and industrial practices using modern smart technologies that enable large-scale machine-to-machine communication (M2M) and the Internet of Things (IoT) providing improved communication, self-monitoring and diagnosis of issues without the need for human intervention. The emergence of the Industry 4.0 revolution can also be seen in food traceability systems where automatic identification (auto-ID) technologies, sensors and communication technologies are integrated for managing food product information throughout food supply chains (Chen, 2017). The emergence of these technologies in food traceability systems is shown in Table 1 and discussed below:

5.1 Barcode

The barcode emerged in the early 1970s and is now considered to be the first auto-ID technology. It has been widely used in many different supply chain management practices (McCathie and Michael, 2005; Tu *et al.,* 2020). A barcode is operationalised as a symbology that encodes information in the form of either one-dimensional (1D) parallel lines (i.e. bars and spaces) or a two-dimensional (2D) matrices of dots (Palmer, 1989; Tu *et al.,* 2020). Barcodes are printed on various types of materials which can be read by special dedicated optical barcode scanners, handheld personal digital assistants (PDA) or smartphones using special application (McCathie and Michael, 2005; Reischach *et al.,* 2011; Tu *et al.,* 2020). When the right infrastructure, software and hardware are in place, the automation provided by a barcode system greatly simplifies information collection, processing and tracking for the users (McCathie and Michael, 2005).

Over the years, many different kinds of 1D and 2D bar code symbologies have been developed, each with its own intended industrial purpose and characteristics, for example, Code 39, Code 128, Data Matrix and QR Code (Musa, Gunasekaran and Yusuf, 2014; Tu *et al.*, 2020). Barcode scanning is considered a reliable form of production identification, owing to its higher accuracy rates and high speeds in comparison to manual data collection (McCathie and Michael, 2005). However, accuracy attained through barcode technology can be compromised by the technology's requirement for using humans to perform scans, leading to potential mistakes (Singer, 2003). Barcode readers require direct 'line-of-sight' for barcode scanning and close-range reading of item one at a time, often making the data acquisition difficult and time consuming. This 'line-of-sight' property leads to more noticeable performance downturn for scanners in harsh environments, such as fog, dirt and rain (McCathie & Michael, 2005). Barcodes are also more vulnerable to security loss, with the cloning or modification of 1D barcode tag information being much easier than for say RFID whose information is not visible to outside.

5.2 RFID

RFID is another auto-ID technology that uses radio frequency signals to identify products and consists of three necessary hardware components: an electronic tag or transponder, a reader or interrogator, and a supervising computer (Tan and Koo, 2014). The primary benefits of RFID, over barcode technology, are: a large tag code offering item-level unique identification; rapid data acquisition simultaneously from multiple tags which enables automatic TRU reading in the production line; non-line-of-sight and no contact scanning which allows tags to still be readable even when encapsulated; security features, such as deep encryption and password protection, to mitigate against security breaches or counterfeiting (McCathie and Michael, 2005).

RFID technology is employed in a number of different systems which vary by the reader transmission frequency, reading range, reading speed, operating environment and cost (RFID4U). The four basic frequency ranges are: LF (low frequency125/134 KHz), HF (high frequency 13.56 MHz), UHF (ultra-high frequency 860-960 MHz) and microwave frequency (2.45 GHz). RFIDs can also be categorised into: passive RFID, semi-passive RFID and active RFID (Tu, Zhou, & Piramuthu, 2020). Passive RFID tags do not possess their own power source and therefore can only send information when energised by encountering with an RFID reader. This results in tags which are smaller, lightweight and less expensive, however, the lack of power supply limits the integration of some wireless sensors which require reliable continuous power to operate. Semi-passive RFID and active RFID tags, with on-tag batteries, provide longer reading ranges, higher data transmission rates and compatibility with a wide range of sensors for recording product physical and environmental data. The on-board power supply and additional functionalities increase the weight, size and cost of these RFID tags, in comparison to passive RFID transponders. RFID tags are also classified by their tag memory programmability, which include: Read-Only; Write Once, Read Many (WORM); and Read-Write.

5.3 NFC

Near Field Communication (NFC) technology also uses radio frequency for data transmission and operates on the same frequency as HF RFID (13.56 MHz) supporting high data transfer rates of 106, 212, 424 or 848 Kbit/s (Mainetti *et al.*, 2013). NFC technology is capable of two-way communications, including data transfer between two NFC mobiles, and one-way communication, with NFC devices and NFC tags, in a similar arrangement to passive RFID. NFC tags do not require a dedicated reader for data transfer; they can be read by any smartphone that has NFC capability. NFC compatible phones are designed to send out short magnetic field pulses at the designated radio frequency, inducing an electric current in the tag's circuit and relaying the information to the phone (Trafton, 2014). Unlike RFID, only one NFC tag can be read at a time and they are capable of read-write programmability.

5.4 WSN

WSN is a network of spatially dispersed and dedicated sensors that collect sensing data of various physical or environmental conditions and communicates them with a base station or central node, from where data is then transmitted to a database server, using an IoT gateway and mobile networks e.g., General Packet Radio Service (GPRS) (Costa *et al.*, 2013; Aung and Chang, 2014). The WSN is built having between a few to several hundred "nodes", where each node, consisting of a radio transceiver with an antenna connection, a microcontroller, memory capacity and energy source, connects to one or several sensors through an electronic circuit.

Although WSN nodes have limited processing capability and memory (Hammervoll *et al.*, 2012), their ability to communicate with each other in various network topologies offsets the impact of missing communication from any single node to the base station, and hence reduces error rate (Costa *et al.*, 2013). This is the main advantage of WSN over RFID systems as RFID devices do not possess cooperative capabilities. WSNs have much longer reading ranges than RFID, due to their ability to relay information from node to node, but are not suitable for identification purposes owing to their inability to transmit product identification (Ruiz-Garcia *et al.*, 2009; Aung and Chang, 2014). A further advantage for the WSN system is the feasibility of installation in places where cabling is impossible, such as within the cargo for monitoring physical and environmental conditions of perishable food (Ruiz-Garcia *et al.*, 2009).

At a reasonable cost and power consumption, WSN can provide real-time information on various parameters, such as the temperature, humidity and vibration experienced by perishable food in transit (Hammervoll *et al.*, 2012). Power consumption can be reduced by placing the sensors into sleep mode after each successful data emission, and only waking up the sensor when required, at regular intervals (Aung and Chang, 2014). Low temperature is known to have a negative effect on the battery life of sensors (Ruiz-Garcia *et al.*, 2009). The ZigBee communication protocol has been proposed to prolong the battery life of sensors. ZigBee is built on the IEEE 802.15.4 standard and supports various network topologies for wireless sensor networks with low energy consumption and low data transmission rates (Óskarsdóttir and Oddsson, 2019).

5.5 EPCglobal standards

EPCglobal is a worldwide association of supply chain partners providing open standards for Electronic Product Code (EPC) and Electronic Product Code Information System (EPCIS). EPCglobal enables effective communication through recording and exchange of product data as products moves through supply chain actors and across country borders (Asher *et al.*, 2007). EPC is unique, serialised identification code format for any kind of product that can be encoded from familiar identifiers, such as Global Trade Item Number (GTIN) and Serialised Shipping Container Code (SSCC). EPCIS is a universal data model for representing the location and state of product as it moves across organisational boundaries, while providing a means for communication between these organisations regardless of the technology suppliers.

The main components of an EPCIS data model include EPC, Event Time, Business Step, Disposition, Read Point, Business Location, and Business Transaction. However, it is often extended in practice to also include Expiration Date, Batch Number, and Temperature. The EPCIS standard is data carrier neutral and can be used to describe data captured from various technologies including RFID tags, barcodes and other data carriers (Asher *et al.*, 2007). The EPCIS databases of different supply chain participants, being connected via local networks or internet, provide a lineage of products movement which is accessible by authorised parties. The accessibility is enabled by deploying a discovery mechanism (e.g., object naming service or ONS) that takes an EPC as an input and replies back the address (in the form of a Uniform Resource Locator, or URL) of an EPCIS repository implemented by the supply chain actor corresponding to the EPC in question (Musa, Gunasekaran and Yusuf, 2014).

The EPCIS framework for an industry is extensible, in that it allows new industry requirements to co-exist alongside the core components while still providing interoperability (Asher *et al.*, 2007). There are no technology implementation standards for EPCIS and there are many solution providers who provide EPCIS compliant technology solutions, using firewalls, encoding, and other safe measures to guarantee the security of the transmitted information (Musa *et al.,* 2014).

5.6 Cloud computing

Cloud computing is the provision of dynamically scalable and often virtualised resources, for example, data storage or software application as a service (SAAS) over the internet (Patil *et al.*, 2012). In practice, cloud computing often refers to internet-based development and use of computing technology. Clouds may be limited to a single organisation, such as enterprise clouds managed by the enterprise IT department, or can be available to multiple organisations, for example public clouds managed by a third party (Wang *et al.*, 2012). The cloud computing architecture comprises three layers: resource, platform and application. The resource layer consists of various hardware used for identification and communication, including personal digital assistants (PDAs), computers, and middleware, which are owned by supply chain operators. Middleware can be described as a software that is the glue or the hidden transition layer bridging the gaps between applications, tools, and databases in order to provide unified services to users (Microsoft Azure, nd). The platform layer includes components such as web servers, application servers, and enterprise service buses, and serves users by providing functionality such as information access. The application layer is the main layer consisting of the applications to serve the users e.g., various internet-based software. Cloud computing provides several advantages for FTSs, including increased scalability, agility, availability, multi-sharing, services in a pay-per-use mode, automated backup, and support for service oriented applications (Wang *et al.*, 2012).

At present, the mainstream traceability systems for food products are often maintained and governed by the government or a leading enterprise by using a centralised cloud-based information system, which participants with accessibility permission can use to input their respective traceability information or to simply access to visualise the data. Such an approach facilitates a common standard database for users, reducing the need for data standardisation efforts by individual companies. However, cloud-based systems may suffer from information tampering, label cloning, product counterfeiting, illegal product trading, accountability difficulty, loss of confidentiality and malicious attack of the central database (Huang *et al.*, 2019; Manning, 2019b).

5.7 Blockchain

Unlike cloud databases managed by central authorities, Blockchain technology provides a distributed database that is participated in, and maintained by, all nodes in a peer-to-peer (P2P) network, or all actors in a food supply chain network (Li *et al.*, 2020). The Blockchain is an immutable, distributed ledger. In practice, this is an ever-growing list of chronologically linked records, called blocks, which store transaction and asset data across many computers throughout the supply chain network. Each block also contains a cryptographic hash of the previous block and a timestamp, so that any involved block in a given connection cannot be altered retroactively, without the associated alteration of all subsequent blocks (Wang *et al.*, 2018). Due to its tamperproof, secure and traceable nature, Blockchains can be deployed effectively in implementing FTSs (Salah *et al.*, 2019). Blockchain is often implemented by deploying a smart contract: a computer programme which defines the protocols of a business contract that governs and controls all interactions and transactions among all the participants involved within a P2P network or supply chain, without the need of a centralised third party (Salah *et al.*, 2019). Blockchain-based FTSs mainly record and merge the product traceability data and transaction information between FSC parties. Each company in the network also maintains their own individual internal traceability database, often using decentralised file systems, which allows linking of internal traceability data with external traceability data in the block and the verification of traceability data integrity (Salah *et al.*, 2019; Li *et al.*, 2020).

Product traceability data is typically stored in decentralised file systems and uploaded to the smart contract platform, which is then broadcast over the whole Blockchain network to ensure authenticity (Huang *et al.*, 2019). Data are verified by the consensus mechanism by other nodes in the Blockchain network before being stored. Trade requests are first verified, before the product ownership is transferred, and any transaction information are packed into a block. Each block is hashed and linked to the next block, making it a secure chain of immutable and tamper-proof records of all transactions, spread across all nodes in the network. In this distributed information system, smart contracts ensure the standardisation of the recorded traceability data (Li *et al.*, 2020). Ethereum, a programmable smart contract platform is popularly used for implementing Blockchain-based information systems among supply chains.

The advantages of Blockchain based traceability systems includes decentralisation, non-tampering protection, data verification, privacy, distributed data storage, transparency and increased trust (Abeyratne and Monfared, 2016; Tian, 2017; Behnke and Janssen, 2020). However, the technology still needs some improvement as it suffers from various disadvantages: Blockchain network can become bulky with time if an unrestricted number of users join, slowing down the addition of new data addition(Behnke and Janssen, 2020); some Blockchain designs do not have any functionality to protect sensitive information from certain users (Feng et al., 2019); Blockchain software written with poorly developed codes is vulnerable to hacking (DeVries, 2016); Blockchain traceability systems can incur high implementation and electricity consumption costs (Li et al., 2019); there is high requirements for training(Behnke and Janssen, 2020); and the technology is not profitably scalable across small supply chains (World Economic Forum, 2019).

Technologies	Technology type	Advantage	Disadvantage
Bar code	Identification technology	• Cheaper compared to RFID and manual paper document. • Easy to use. • More reliability, high speed and accuracy than manual methods	• Line-of-sight data reading • Risk of optical damage • Less accuracy compared to RFID. • Time consuming for one-by-one tag data reading • Shorter reading range than RFID • More vulnerable to security loss in comparison to RFID
Radio frequency Identification (RFID)	Identification technology	• Line of sight is not required • Longer reading range, high speed reading and high accuracy • Store larger amount of data • Tag durability • Multiple tag reading at a time increases automation • Higher data security than barcode	• Not profitable for low value items. • Cost of infrastructure is high • High expertise or training required • Tag collision may occur
Near Field Communication (NFC)	Identification technology	• Line-of-sight data reading is not required • Carries more data than bar code • Wireless data transfer • No need of dedicated reader as mobile phones can be used • Offers read-write programmability for tag data	• Not profitable for low value items. • High expertise or training required • Slow reading rate than RFID as multiple tag reading is not possible • Technology is not matured yet.
Wireless Sensor Network (WSN)	Physical and environmental property recording technology	• Wireless product physical and environmental data collection • Higher reading range than RFID • Cooperation among multiple data collection nodes	• Cannot provide product identification • Expensive for low value item • High expertise or training required
EPCglobal	Identification and communication standards	• Standards for product identification code and database • Interoperability in external traceability information communication • Easily scalable	• No technology standards are defined • Difficult to adopt for manual traceability system • No standards for sensor data

Cloud computing	Communication technology	• High scalability • Agility and high availability • Multi-sharing of databases • Services in the pay-per-use mode • Automated backup of traceability database	• Cannot provide data authentication • Vulnerable to single node attack • May suffer from information tampering and label cloning • Not possible to delegate accountability for data • May encounter Loss of confidentiality and malicious attack
Blockchain	Communication technology	• Provides transparency, trust and authenticity • Does not require centralised third party • Eliminates the requirements for large data sharing on product tag	• Slow information recording • Susceptible to system hacking • Expensive for low value items and small holders • Difficulty with technology scalability • High expertise or training required

Table 1. Traceability technologies with advantages and disadvantages

6. Barriers in implementation of effective FTS

Despite the enormous potential of emerging technologies to improve traceability, various barriers exist that hinder their implementation in FTSs. Some of these barriers are discussed below:

6.1 Lack of awareness

There is a lack of understanding of the theoretical traceability concepts, and how traceability differs from other similar concepts such as chain of custody (Olsen, 2017). For example, a United Kingdom (UK) survey of small and medium sized food and drink industries shows that only 25% of participant companies align the term "traceability" with information and product logistics that leads to reduced effectiveness of their traceability systems and implementation (Mattevi and Jones, 2016). In addition, there appears to be widespread resistance to the implementation and use of new technologies, with many FBOs still relying on manual traceability systems. Many FBOs are not aware of all the potential benefits of implementing improved traceability, seeing only the additional upfront capital investment and legal requirements. Instead, they persist with paper-based one-up-one-down traceability systems, which are limited only to identification of suppliers and customers (Asioli, Boecker and Canavari, 2014)**.**

6.2 Resource deficiencies

A barrier to improved practical food traceability results from resource deficiencies and a lack of funding, as traceability implementation is expensive and complicated (Bosona and Gebresenbet, 2013). The allocation of costs and benefits among food supply chain partners, during traceability implementation, requires considerable effort and results in initial resistance against implementation. The introduction of new FTSs also requires increased administrative work, training and capacity building, especially when companies are implementing traceability systems for the first time (Bosona and Gebresenbet, 2013).

6.3 Inefficient data management

Inefficient information flow in FTSs has been revealed, in practice, by recurrent food crises (Badia-Melis, Mishra and Ruiz-García, 2015). Inefficient information flow is associated with poor traceability data management in individual FBOs' internal FTSs (Duan *et al.*, 2017). Information loss for an FBO occurs when the product and its operational or quality information are not systematically recorded or linked at the key information collection points (Karlsen *et al.*, 2011; Zhang and Bhatt, 2014). This can happen as a result of failure in TRU identification and transformation recording, incompetent recording techniques, absence of industry specific standard data lists, and simply human error (Bertolini *et al.,* 2006; Karlsen *et al.,* 2011; Zhang and Bhatt, 2014; Karlsen and Olsen, 2016).

6.4 Lack of standards

Various food supply chain operators generate an increasing amount of traceability data using various technologies, which is essential for effective traceability. For example, a farm may use simple paper trails for data recording, while processors are equipped with enterprise resource planning (ERP) software. However, the prevalence of heterogeneous data sources, means a traceability system may face significant interoperability challenge and data integration issues (Bougdira *et al.,* 2019). This issue is amplified by the lack of a widely adopted standard for how FBOs record and transmit data for traceability, which in turn, hinders adoption of novel communication technologies (e.g., Blockchain) (World Economic Forum, 2019).

6.5 Technology cost and scaling issues

Cost is often considered to be the main constraint preventing the more widespread use of ICT and Industry 4.0 technologies (e.g., RFID, WSN, Blockchain), especially in the case of low value items procured from smallholders. Some technologies (e.g., Blockchain) do not appear profitable for small scale food supply chains due to its high set-up cost (World Economic Forum, 2019). However, the upfront costs of implementing improved traceability systems using novel technologies is frequently considered in isolation, as an additional cost, without weighing this against the potential cost reduction through ensuring the safety, quality and authenticity of food products. This is because the benefits of improved traceability and the reduction in risk to the food supply, are challenging to price. There is an urgent need for scientists and practitioners to co-develop new tools to assess the risks and potential costs of not implementing more advanced traceability systems.

7. Improvement pathways

To adopt new technologies and achieve desired outcomes, new pathways need to be created which drive improved traceability. Some improvement pathways and policy interventions are outlined below:

- Multi-stakeholder collaborations combined with financing and policy incentives need to be developed that can support FBOs in adopting emerging technologies that would otherwise necessitate high capital investments and operational costs beyond the reach of such organisations (World Economic Forum, 2019).

- Ongoing technological development needs to be supported through policy intervention to drive down the costs of adopting more advanced traceability solutions. An example can be the "Contract for Difference (CfD)" of the UK government to reduce prices of renewable electricity technologies (Evans, 2017).

- Technology and data format standards are available for national animal traceability in many countries (Charlebois *et al.*, 2014). Similar standards from GS1 can be embedded in the legal requirements for traceability of food which are more vulnerable to fraud e.g., olive oil and seafood (Mermelstein, 2015).

- Sector specific clear, consistent and globally harmonised standards should continue to be developed such as ISO 12875:2011 and 12877:2011 for captured and farmed finfish (Olsen, 2017).

- New tools and frameworks for assessing the risks and potential costs of food quality loss and safety breaches, against the investment costs in advanced traceability systems are required to be developed for encouraging more advanced FTSs.

8. Where to look for further information

The following articles provide a good overview of the subject discussed in this chapter:

- Islam, S., & Cullen, J. M. (2021). 'Food Traceability: A Generic Theoretical Framework', Food Control, 123, 107848.

- Badia-Melis, R., Mishra, P. and Ruiz-García, L. (2015) 'Food traceability: New trends and recent advances. A review', Food Control, 57, pp. 393–401.

- Bosona, T., & Gebresenbet, G. (2013). 'Food traceability as an integral part of logistics management in food and agricultural supply chain'. Food Control, 33(1), pp. 32–48.

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