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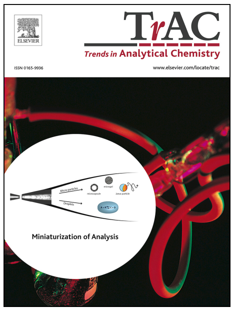

Future challenges on the use of blockchain for food traceability analysis

Juan F. Galvez, J.C. Mejuto, J. Simal-Gandara

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Future challenges on the use of blockchain for food traceability analysis

(Blockchain in food traceability)

Juan F. Galvez [a] (galvez@uvigo.es)
J.C. Mejuto [b] (xmejuto@uvigo.es)
J. Simal-Gandara [c,*] (jsimal@uvigo.es)

[a] Department of Informatics, ESEI, University of Vigo – Ourense Campus, Ourense (Spain).
[b] Department of Physical Chemistry, Faculty of Science, University of Vigo – Ourense Campus, Ourense (Spain).
[c] Nutrition and Bromatology Group, Department of Analytical and Food Chemistry, Faculty of Science, University of Vigo – Ourense Campus, Ourense (Spain).

[*] Corresponding author (jsimal@uvgo.es)

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Abstract

The steady increase in food falsification, which has caused large economic losses and eroded consumers' trust, has become a pressing issue for producers, researchers, governments, consumers and other stakeholders. Tracking and authenticating the food supply chain to understand provenance is critical with a view to identifying and addressing sources of contamination in the food supply chain worldwide. One way of solving traceability issues and ensuring transparency is by using blockchain technology to store data from chemical analysis in chronological order so that they are impossible to manipulate afterwards. This review examines the potential of blockchain technology for assuring traceability and authenticity in the food supply chain. It can be considered a true innovation and relevant approach to assure the quality of the third step of the analytical processes: data acquisition and management.

Keywords: blockchain; food authentication; agricultural and farming applications; food chain; traceability; data analysis and management.

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1. Blockchain fundamentals

Blockchain technology emerged in 2008 as a core component of the bitcoin cryptocurrency (Bhardwaj and Kaushik, 2018). Blockchains provide transactional, distributed ledger functionality that can operate without the need for a centralized, trusted authority. Ledger recorded updates are immutable and cryptographic time stamping affords serial recording. The robust, decentralized functionality of blockchains is very attractive for use with global financial systems but can easily be expanded to contracts or operations such as tracking of the global supply chain. Three papers from the 1960s established specific principles that subsequently materialized in the blockchain concept. Thus, Haber and Stornetta (1991) described how to use crypto-signatures to time-stamp documents; Ross Anderson (1996) proposed a decentralized storage system from which recorded updates could not be deleted; and Schneier and Kelsey (1998) described how to encrypt sensitive information in order to protect log files on untrusted machines.

A blockchain is essentially a distributed database of records in the form of encrypted “blocks” (smaller datasets), or a public ledger of all transactions or digital events that have been executed and shared among participating parties, and can be verified at any time in the future. Each transaction in the public ledger is verified by consensus of a majority of participants in the system. Once entered, information can never be erased. The blockchain contains a certain, verifiable record of every single transaction ever made and its blocks can be used to coordinate an action or verify an event. This is accomplished without compromising the privacy of the digital assets or parties involved. In order to prevent third party sources such as banks, governs or social networks from being hacked, manipulated or compromised, this technology uses mathematical problems that require substantial computational power to solve (Nakomoto, 2009). This protective measure makes it harder for potential attackers to corrupt a shared database with false information unless the attacker owns most of the computational power of the overall network. Consensus within the network is achieved through different voting mechanisms; the

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most common of which requires certain computers on the network, colloquially referred as “miners”, to solve a computationally intensive mathematical problem, and other computers to verify that the solution to the problem does not correspond to a previous transaction. This mechanism is called “Proof of Work”. Every computer (node) in the network stores a copy of the blockchain, and the nodes are periodically synchronized to ensure that all are sharing the same database. In this way, blockchain protocols ensure that transactions are valid and never recorded to the shared repository more than once; thus enabling people to coordinate individual transactions in a decentralized manner without the need to rely on a trusted authority to verify all transactions (Bonneau et al., 2015; Wright and De Filippi, 2017). Bitcoin is the most popular example intrinsically tied to blockchain technology. However, the blockchain concept can be applied to any online repository where a certain trusted authority is needed (Crosby et al., 2016).

Blockchains enable end-to-end traceability by bringing a common technological language to the food chain, while allowing consumers to access the story of foods on their label through their phones. This has raised the need to trace products through the complex supply chain from retail back to the farm: to trace an outbreak; to verify that a product is kosher, organic or allergen-free; or simply to assure transparency to consumers. When applied to the food supply chain (Charlebois, 2017), digital product information such as farm origination details, batch numbers, factory and processing data, expiry dates, storage temperatures and shipping details are digitally connected to food items and their information is entered into the blockchain at each step of the process. All members of the business network agree upon the information acquired in each transaction. Once consensus is reached, no permanent record can be altered. Each piece of information provides critical data that may potentially reveal food safety issues with the product concerned. The record created by the blockchain can also help retailers to manage the shelf life of products in individual stores, and further strengthen safeguards relating to food authenticity. Across ecosystems, business model changes enabled by blockchain technology can bring strengthened trust and transparency, and a new link to value exchange. Whether it is individuals seeking to complete transactions involving many parties, or enterprises collaborating across

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multiple organizational silos —wherever any documents or transactions must be confirmed, settled, exchanged, signed or validated—, there are usually frictions that can be avoided by using blockchain technology to unlock greater economic value. One of the greatest challenges in implementing a blockchain system is its usual complexity (Iansiti and Lakhani, 2017). Thus, all stakeholders in the chain must collaborate to adopt and implement the technology in order to make it fruitful. Because blockchain technology is still at an incipient stage of development, there is a general lack of standards for implementation (**Fig. 1**). A blockchain should be universal and adaptable to specific situations (Hyperledger, 2016, 2017). In addition, the need to agree on a given type of blockchain to use places the parties involved under pressure. This is a major disadvantage at a time when blockchain technology is progressing fast, and predicting the best choice for the future is rather difficult. One other disadvantage of blockchain technology is that it has scarcely been applied to the supply chain (Iansiti and Lakhani, 2017). In fact, little has so far been done to push this still immature technology, which will require strong motivation, close collaboration and system integration to operate smoothly. **Table 1** summarizes existing blockchain-based solutions to traceability problems.

2. Security in blockchains

As can be seen from **Fig. 2**, data can be secured at a variety of levels by using various types of objects (Leibowitz, 2016), namely:

- *A locally stored digital fingerprint* (Lifton, 2016). An organization may store digital fingerprints (hashes) locally but separately from the original files or content in order to make it easier to confirm whether data have been changed or manipulated within a given organization.
- *Digital fingerprints stored in a local hash tree*. A system can be made even more robust by storing each hash in a “hash tree” or “Merkle tree” (Merkle, 1982). Each hash is combined with previous ones into a single, new hash in order to make it very

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difficult to alter the previous hashes without knowing that something has gone wrong. Controlling changes in internal data is thus made much easier as well.

– *Digital fingerprints in an external hash tree*. The solution can be made trustworthy by having an external institution control the hash tree. This makes it significantly more difficult for the organization possessing the original files to make changes without the other parties knowing. The Swedish firm Scrive allows e-signing of documents such as contracts between parties that can be verified by an external partner (Scrive, 2018). Processes can also be controlled by having the external host of the hash tree to separate validated hashes correctly following prescribed processes. This affords some form of “smart contracts” (Gord, 2016).

– *An external hash tree in a distributed ledger structure*. The hash tree can be protected from having a single point of failure by creating a shared database —a distributed ledger shared among the participants (Mattila, 2016; Pinna and Ruttenberg, 2016). With this solution, no single employee or organization can manipulate verifications in the database or processes. This allows for sensitive transfers such as financial transactions or transactions where it is unwise to rely on a single manager of the database. This level of security is needed for trading CO_2 emissions in a blockchain, for example. It is unwise to have a single point of failure of data that are easy to monetize.

– *An external hash tree in a public consensus database structure* (Dunkel, 2015; Shermin, 2017). In a public distributed ledger or blockchain, anyone can be part of the validation process. None is in control of the system, but power to make changes is given to those running the system and providing most security to the solution. Public institutions cannot control the process, which is one of the benefits but also one of the problems. For example, there is no protection for those who lose their assets or their IDs. This risk can be mitigated by having custodians (*viz.*, individuals storing the private keys that lend access to digital assets), but custodians can be hacked too. The

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distributed ledger may therefore be highly secure, but the ecosystem around the solution may be vulnerable. Public blockchains for traceability and control of goods such as food are seemingly pointless. Only private blockchains of this type (*e.g.*, Bitcoin, Ethereum) are feasible owing to the high transaction costs involved and the low capacity of public blockchains.

– *Hybrid distributed ledgers* (Shermin, 2017). The limited transaction and storage capacity of public blockchains has raised efforts to create hybrid structures where most transactions are made outside the public blockchain and confirmations of groups of transactions are connected to it.

Solutions 1 to 5 can all be implemented in a secure blockchain.

Blockchain technology can affect business trust (Kim et al., 2008; Aljazzaf et al., 2010), in at least five different ways, but not all need be present in every case. Thus, both the protocol layer and the business layer of the blockchain affect trust. Two mechanisms stem from the protocol layer: transparency and security. These two are increased by the characteristics of the technology, namely: public–private keys, and immutable transaction history, increase transparency as it is clear who has done what to the data. Similarly, encryption and decentralization can increase security as they make systems safer and more private. Transparency and security in turn affect trust. In addition, specific rules for a blockchain pertaining to the business layer can place restrictions on users to increase trust or make it irrelevant (**Table 2**).

3. Authentication of food products

Food authentication is a process by which the compliance of foods with their label descriptions (*e.g.*, geographic origin, production method, processing technology, composition, etc.) is verified. The declaration of specific quality attributes in expensive products is of particular interest because they are often the targets of fraud. Food fraud no only causes economic losses, but also is a threat to human health (*e.g.*, if banned ingredients are toxic or contaminated with

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pathogens, or if non-declared substitutes and production processes cause health problems such as allergic reactions) (Gerbig et al., 2017). Evidence of provenance is important to ensure food quality and consumer protection, and so is compliance with international standards and guidelines (Danezis et al., 2016). Labelling regulations play a crucial role in determining which scientific tests are appropriate for a particular issue (Esteki et al., 2017). Consumers around the world are increasingly demanding reassurance that the origin and content of their food complies with the information on the label. This is why consumers, producers and regulatory bodies have recognized the authenticity of food products as an important quality criterion. Rapid, specific methods for detecting adulteration, verifying quality, and guaranteeing geographic origin and type of production of food products are currently in wide demand (Rodríguez-Bermúdez et al., 2018). The analytical techniques most commonly used to authenticate food include the following:

- Spectroscopies (MIR, NIR, Raman, NMR, UV–VIS).
- Separation techniques (GC, HPLC, electrophoresis).
- Mass spectrometries (MS, MS/MS).
- Stable isotope measurements (IRMS).
- DNA–PCR methods.

Measuring ratios of stable isotopes can be used for discriminating foodstuffs according to geographic origin or technological processes. Determinations of the isotopic ratios of the light elements hydrogen (δ2H), carbon (δ13C), nitrogen (δ15N), oxygen (δ18O), and sulphur (δ34S) in combination with those of heavy isotopes (δ87Sr) and trace elements have allowed the origin of food products to be established (Podio et al., 2013). Mid- (MIR) and near-infrared (NIR) spectral signatures typical of some constituents are obtained that may be considered to be “fingerprints” of the food that contains them (Pizarro, Rodríguez-Tecedor, Pérez-del-Notario, Esteban-Díez, & González-Sáiz, 2013). Chromatographic methods are also widely used to record the fingerprints of foodstuffs. Gas chromatography (GC) and high performance liquid chromatography (HPLC) afford high-resolution separation of compounds. They can be used in combination with various types of detectors including diode array (DAD) and mass spectrometric detectors in hyphenated techniques such as GC–MS, GC–MS/MS, LC–MS and

LC–MS/MS. Mass spectrometers are now highly sensitive and universal, and can detect almost any organic compound irrespective of class and structure. Like spectroscopic profiles, chromatographic profiles may be used as fingerprints of foods to control their quality and guarantee their authenticity (Gao et al., 2012). DNA analysis has been progressively used in food science to meet various needs such as GMO detection, microbial pathogen determination or detection of undeclared allergenic ingredients (Sforza et al., 2011). These analyses use nucleic acids probes such as the polymerase chain reaction (PCR), which allows trace amounts of degraded nucleic acids to be detected and their sequence established. These methods may also be useful to identify meat or fish species and to recognize genetically altered foods (Meyer & Candrian, 1996).

Because different fingerprints are based on also different physical and chemical principles (Zhang, Zhang, Dediu, & Victor, 2011), each fingerprinting technique has its own intrinsic strengths and weaknesses. Fingerprinting chromatography technology is perfectly suitable for food authentication in-house. When method transferability is needed for acceptance by authorities, producers and consumers, food reference materials should be used to normalize fingerprinting signals across equipment (Cuadros-Rodríguez, Ruiz-Samblás, Valverde-Som, Pérez-Castaño, & González-Casado, 2016). Compositional information on significant chemical markers may be subsequently used to confirm authenticity and assure transferability. Chromatographic fingerprinting in combination with chemometric techniques is a powerful tool for detecting food fraud. Thus, consumers and producers are placing a high value on accurate labelling, and providers are now proactively providing consumers with clear labelling, traceability and transparency. Accurate, robust, efficient tools must be made available throughout the food chain to verify the nature of the food if transparency, efficiency and safety are to be assured. Such tools should permit the transparent and efficient control of safety in both raw materials and products in accordance with production standards.

In the first quarter of 2017, Walmart implemented a pilot test of blockchain technology co-developed by IBM to track produce in the US and pork in China (IBM, 2017). When a customer becomes ill, it can take days to identify the product, shipment and vendor. With its blockchain, Walmart will be able to obtain crucial data including suppliers, details on how and

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where the food was grown and who inspected it from a single receipt. The database extends information from the pallet to the individual package. If the pilot projects succeed, the technology is likely to be the way of the future. Since a blockchain can store the history of all transactions ever made and allows one to recreate the history and identify the origin of a product, blockchain technology can be useful to support a traceability system in line with the definition of Pizzuti and Mirabelli (2015). In fact, blockchains can be useful as traceability systems by virtue of the ability to detect and identify specific products within a few seconds even though the same result could be achieved with a well-performing centralized system. Expeditiousness is usually important, but even more so with food (e.g., when a source of contamination must be identified). Establishing an effective traceability system based on a centralized system requires ensuring information connectivity among all partners (Bosona and Gebresenbet, 2013) since one of the parties will be responsible for all data.

4. Advantages of applying the blockchain concept to the food supply chain

All stakeholders involved the food supply chain (farmers, distributors, packers, processors, grocers, restaurants, traders) are driven by a need to demonstrate customers the superior quality of their methods and products (Smith, 2008). Blockchain simplifies this challenging task by providing for one-to-many data integration and process orchestration among participants. In addition, it provides a lexicon and ontology for describing attributes of our food through the supply chain. This in turn facilitates establishment of a data structure that can be used by smart contracts to automate assertions, certifications and market operations. There are three elements to explain why the food supply chain can benefit from the blockchain concept, namely: transparency, efficiency, and security and safety.

4.1. Transparency

The primary aims of a blockchain are to facilitate the exchange of information, create a digital twin of the information and its workflow, and validate the quality of food as it moves along the

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chain (World Economic Forum, 2017). These aims are accomplished by allowing each participant to share assertions, evidence and evaluations of each other's assertions about the food. The journey of food along the supply chain is captured in a blockchain object called a "food bundle". At the end of the journey, the bundle is the combination of all information contributed by the stakeholders over the lifetime of the food item. This information can then be used to establish the provenance, quality, sustainability, flavour and taste profiles, and many other attributes of the food.

4.2. Efficiency

A blockchain is a piece of infrastructure that enables new transactions between players not knowing or trusting each other yet. Smart contracts are instructions that interface with the blockchain protocol in order to automatically evaluate and possibly post transactions in the blockchain (Raskin, 2017). Similarly, smart libraries are specialized sets of blockchain-aware functionality that can be used locally or privately, or shared and licensed to other blockchain participants and agents. All participants come together in the blockchain, can evaluate the assertions made, and notify their account holders when matches in quality, timing, quantity, etc., are found. Buyers and sellers are matched by a shared but trusted need for data, which can then be combined and used by either party. In this way, traceability does not have to wait for large company consortiums to use standards, and/or semi-mandatory or concentrated business practices, to access the information.

4.3. Security and safety

Blockchains can also be used to issue and manage the creation of unique cryptographic tokens (Nyström, 1999). The tokens can be made to represent value in escrow between two participants (*e.g.*, future production to be farmed in a particular field lot). In fact, tokens need not take the form of value exchange for financial settlements of invoices and contracts. Rather, they represent a license to publish information that becomes uniquely valued in proportion to the needs of

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others in the blockchain. For example, in-field sensors, drones and precision spraying equipment are expensive to purchase by farmers. A token strategy may encourage growers to publish information produced by these devices and machines with tokens to defray their purchasing and implementation costs. The strategy around the issuance of these crypto-tokens, which need not be implemented in the initial system, is still being defined, however.

5. Blockchain uses in different food sectors

Properly managing the supply chain, and hence the human actions it involves, entails having all partners agree on the data to be stored in the blockchain from raw materials to end-products. The main goal is to select information that is relevant to all parts of the supply chain —with special emphasis on consumers’ requirements— as well as appropriate standards. In addition to serving the functions of a traceability system, a blockchain can be used as a marketing tool. Because blockchains are fully transparent (Iansiti & Lakhani, 2017) and participants can control the goods in them (Liao et al., 2011; Storoy et al., 2013), they can be used to improve a company’s image and reputation (Fombrun, 1996; Carter & Rogers, 2008), boost loyalty among existing customers (Pizzuti & Mirabelli, 2015) and attract new ones (Svensson, 2009). In fact, companies can easily distinguish themselves from competitors by emphasizing transparency and monitoring of product flow along the chain. In addition, rapidly identifying a source of food contamination can help to protect a company’s brand image (Mejia et al., 2010) and alleviate the adverse impact of criticism from the media (Dabbene & Gay, 2011).

With the globalization of trade, supply chains are becoming increasingly complex and tracing objects through their complex webs is being increasingly difficult. In fact, the actual relationships among stakeholders are often complex (**Fig. 3**). Thus, suppliers can be classified into tiers, with a first-tier supplier providing the organization directly with, for example, metal cans, and a second-tier supplier such as the provider of the raw materials needed to produce the cans (Bozarth & Handfield, 2006). Organizations typically have many suppliers in different tiers involved in a specific product; also, the suppliers are commonly non-exclusive to a particular

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organization. Aung and Chang (2014), and Golan (2004), have set three main objectives for traceability, namely: (1) better supply chain management, (2) product differentiation and quality assurance, and (3) better identification of non-compliant products. One additional driver for assuring traceability is complying with applicable regulations and standards.

Most existing blockchain systems for traceability management have been developed since 2015 (**Table 3**). For example, the AgriOpenData Blockchain integrated system (2016) is an innovative digital technology guaranteeing traceability in the whole agri-food chain and in the processing of agricultural products in a transparent, secure, public manner (see **Fig. 4**). This is particularly the case with “bio” and DOCG (Designation of Origin Controlled and Guaranteed) products, which are amenable to certification of their quality and digital identity (viz., provenance, ownership, seeding, treatments, crop, Internet of Things analysis, processing, storage and delivery). This digital history of organically grown products assures authenticity to end-consumers and enhances the quality of the agri-food business. Some special FruitChain protocols (Pass & Shi, 2017) allow the variance of mining rewards, and hence the need for mining pools, to be substantially reduced. For example, in allocating space for 1000 fruits per block in a FruitChain where each fruit takes 80 bytes requires using roughly 8% of a 1 MN block. This allows a solo miner to obtain its first rewards 1000 times faster (in a day or several rather than a few years). In addition, DNA samples from an animal can be used to identify its breed, but additional information such as country of origin, exposure to toxins and unregulated medication, among other key markers, can be collected. These data can be crosschecked with the blockchain record to assure the animal’s authenticity and lifecycle (Arc-net, 2017).

Transparency will no doubt be of future value, especially in connection with sustainability and the environment (Mol, 2015). This is a field, in which customers’ demands have grown considerably in recent years (Trienekens et al., 2012). In fact, customers’ confidence relies on transparency; and, according to Beske-Janssen et al. (2015), transparency is the key to assessing performance in a supply chain. Although one can use a centralized system to be transparent simply by disclosing information, blockchain technology is superior in this respect.

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The strength of blockchain transparency lies in trust; thus, no transaction can be changed or manipulated after it has been recorded —with a centralized system, outsiders cannot assess the trustworthiness of disclosed information. The idea behind blockchain technology is that, once data have been chronologically stored and verified, they cannot be manipulated without altering the entire history of the blockchain. In other words, once a transaction is made it is irreversible. It is important that the information be accurate and reliable (Gualandris et al., 2015) since, for example, information about an order must be retrievable upon request. This is one other advantage of blockchain technology over centralized systems in terms of trustworthiness.

Blockchains can be of help to address environmental and social concerns (Provenance, 2015, 2016). This is a result of blockchain technology supporting traceability and transparency, which can be further strengthened by integrating smart contracts. For example, a company can lower the risk of hauliers using trucks with an emission standard lower than agreed. In addition, blockchains can be extended to collective agreements.

With the rapid development of blockchain technology, building a decentralized system the information in which can be completely trusted is the obvious development pathway for the logistics industry (Tian, 2016). Provided application costs can be significantly reduced, Radio Frequency Identification (RFID) technology will be more widely used in the logistics industry. No doubt, a widespread use of these emerging technologies can lead to better understanding, transport, verification and assurance of products as they travel along the supply chain, and this can effectively enhance the quality and safety of agri-food products.

6. Blockchains at different steps in the food supply chain

As can be seen in **Fig. 5**, the traceability inherent in blockchains can be accomplished at all stages of the food supply chain.

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6.1. Production

Harvested crops can be packaged, labelled with RFID tags and entered into a system by storing relevant information in profiles. Such information may include background environment (e.g., soil, water, air and sunlight quality); plant cropping conditions (e.g., quality of seeds, working practices, variety, item number, production area, growing conditions, planting time, plucking time, staff involved); and application of fertilizers and pesticides (De Meijer, 2016). A new trade can be started between the producer and processor where products will be exchanged after signing a digital contract that is stored in the blockchain.

6.2. Processing

Processing enterprises can read and enter new data into a product's profile by, for example, scanning its tag. The information may include processing environment (e.g., temperature control, disinfection, processing equipment); additives used and relevant staff (Crossey, 2017). In addition, new tags can be attached to end-product packages.

6.3. Storage

Using Internet of things (IoT) equipment allows information about received products to be easily obtained. In fact, wireless sensors and monitoring equipment allow real-time storage information about a product (e.g., quantity, category, temperature, humidity, storage time) to be checked and updated in both the product's profile and its tag. This system can also help an enterprise to fulfil its dynamic storage management requirements (Heinen, 2017). For example, managers can make decisions as to which specific products should be given priority for removal in order to avoid losses or spoilage.

6.4. Distribution

Assuring food safety and quality at the distribution stage entails adhering to the principle "time, temperature and tolerance". Setting temperature and humidity sensors in different temperature

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areas of refrigerated containers, using vehicle-mounted wireless networks and computers, can establish a monitoring system. Real-time environmental data for products including temperature and humidity can thus be added to digital profiles and tags at regular intervals. An alarm will be immediately raised if the temperature or humidity exceeds the security standard, for example. Also, by using GPS technology, a distribution centre can implement vehicle positioning for each refrigerated truck and optimize its route to shorten delivery times (Filiba, 2017).

6.5. Retailers

When retailers receive products, they obtain full information about the supply chain (Lumb, 2017). Consumers can then use an RFID reader to obtain the information about such products when shopping. Thanks to blockchain technology, all information produced along the supply chain is auditable, with details about the products, in a real time by inspecting the traceability system. The system can also be used to monitor the freshness lifetime of products so that retailers can replace them close to their expiry date. In addition, if a food safety incident occurs, the defective products involved can be immediately located thanks to the traceability inherent in the blockchain. Reasons, location and responsible staff can be easily traced, and losses and hazards reduced largely, as a result.

6.6. Administration

Certification and auditing authorities, and government departments, can visit the working field at random times to check whether rules and regulations are matched, or whether relevant data have been tampered with before being updated by the participants. The results of the inspection should be recorded in digital profiles of both parties (Fraser, 2017).

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7. A typical food traceability case study

Global Traceability Standard provides various points in the supply chain, for instance the trade items, logistic units, parties and locations, with unique identifiers. Automatic data capture techniques such as barcodes and RFID-tags are used on products or pallets across the supply chain to gather the traceability data based on the activities in the supply chain. DNA markers and isotope tests are emerging techniques to address traceability of food with random sample test. Analysis of a DNA sample from an animal is able to provide key markers: its country of origin for example. A digital copy of that DNA can then be attached to every item or product a company creates, which brings traceability to the item level, rather than to an entire batch. As a result, there is the ability to track each item throughout the supply chain. Subsequently, the digital marker can then be crosschecked with the block chain record to ensure the product's authenticity throughout its life cycle. The process allows producers to create a chain of custody. Once the food lands on a retailer's shelf, consumers can scan a QR code on the food package with their mobile phones to receive food safety information about the product, including details as to what is in the package and its origination. This process helps organisations prevent fraud while delivering total traceability, cutting the costs of product recalls and reducing process inefficiencies. It ensures that retailers can guarantee the authenticity of the food that reaches their shelves. This has helped to expose the enormous potential of blockchain and the digital for ensuring food supply-chain transparency and traceability as well as tacking the significant challenge of food fraud in the 21st Century.

A complete traceability system will include components that manage (GS1, 2017):

1. Identification, marking and attribution of traceable objects, parties and locations.
2. Automatic capture (through a scan or read) of the movements or events involving an object.
3. Recording and sharing of the traceability data, either internally or with parties in a supply chain, so that visibility to what has occurred may be realized.

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With complex and long supply chains, characterized by numerous intermediary and lacking transparency and insufficient supporting systems and digitalization, many challenges still remain. Automatic data capture techniques is often costly, hard to implement and difficult to apply to volumes and bulk items. The challenge of traceability is simply a lack of records. Increasingly complex products require more complete traceability systems. Manual written documents lead to human error, difficulties in quickly sorting products and slow trace back/forward ability. The way forward is electronic data management systems and digitalization of the processes.

7.1. A plant food case

Production Contract records every stage from origination information, purchasing raw materials, farming or planting to harvesting. RFID tags are used on agricultural machineries and vehicles to trace their schedule. Sensors are used in an IoT model to track fertilization and pesticides condition. Smart contract then based on its predetermined conditions, weather forecast water, soil and other production conditions to decide operation of agricultural machineries and vehicles. Processing contract is another key role of the food traceability system. Processing manufactories can fetch production data by looking up the distributed ledger. After processing, the related data are uploaded through RFID tags again immediately. Delivery contract relies on IoT sensors with wireless network connection. The shipping time and arrival time are written in the blockchain in real time. With GPS positioning the location of the delivery plane, ship or truck, managers can easily trace back once accident occurs. Cold chain distribution much more concerned about temperature and humidity, if one of them reach the limit regulated on the smart contract, manager will be notified by alert to adjust the delivery condition. Sales contract is the last step of food traceability system. Consumers scan the bar codes to obtain the data from production, processing to delivery. A typical food resume includes batch number, verification mark, producer, expiration date and barcode. Transparent food information not only enhance food traceability, but also increase consumers' confidence and activate their will to buy trustworthy food (Tian, 2016).

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7.2. An animal food case

A project of collaboration between Walmart, IBM and Beijing Tsinghua University, aimed to create a model using blockchain technology for food traceability, supply chain transparency and auditability, was planned to track and trace Chinese pork (Redman, 2016). The project is using the IBM and Linux Foundaton-led Hyperledger Project architecture. Food production flow can now be digitally tracked in an immutable environment under the distributed ledger framework. The tracking information includes storage temperatures, expiration date, shipping details, origination farm details, batch number and much more relevant data when the food being delivered worldwide. The data are digitally connected to food items and the information is entered into the blokchain along with every step of the process. In the future, the Government will use the information management of food safety to link up cross-sector information systems related to food management, from the examination, border inspection and food industry-registration system into a "food cloud".

8. Future challenges to innovation in blockchain technology

The Global Food Traceability Centre has identified the following issues that are faced when trying to execute food traceability:

1. Rapidly shifting consumer preferences. Consumers demand rapid access to reliable and relevant information whenever they want it. There is also an increasing level of discomfort regarding product recalls. Their confidence is fragile. There is the power of social networks, which cannot be overlooked.

2. There are many overlapping and conflicting demands from national regulators around the world. Different regulations on allergens, trace elements, pesticides, etc. Global sourcing means that time zones play a significant role in response times. Food fraud and market substitution for economic gain is also a global challenge.

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3. Another challenge is the lack of unifying requirements. Current internal systems do not provide a means for reliable and rapid response to trace back data across the food chain. Additionally, data can be difficult to analyse into relevant decision-making formats.

4. Traceability varies by industry and product. There are a number of consistent principles:

- In Agriculture/Farming/Fishery: Identification starts with birth of livestock or planting of produce/grain and follows through the growth process, use of pesticide, nutritional records, vet records and transportation to market
- For Food Manufacturers/Processors: Identification starts at the source for each ingredient and follows through processing, packaging, distribution and transportation
- In Retail and Foodservice: Identification starts with receiving receipts/invoices to identify lot and batch information with regulations not requiring tracking “one-up” to final consumer
- In Transportation and Distribution: Commingling points of contact are vectors for spread of disease. Waybills should contain source party and target party identification. Specific locations are needed for livestock in most countries. If products are disaggregated for smaller shipments, then records need to reflect lot/batch codes of the manufacturer or processor.

5. In many cases, the challenge is simply a lack of records. There is a need to move toward electronic data management systems. Readability of written documentation leads to the following:

- Human error
- Difficulties in quickly sorting product
- Slow trace back/forward ability

6. Weak technical systems prohibit rapid response times. The usability of some technical solutions for small and mid-size firms are questionable. Low cost and effective solutions are available via numerous software solution providers. However, interoperability, different systems talking to each other, must be addressed.

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Overcoming these challenges is essential to the successful use of traceability to maintain the safety of the food supply. A large number of blockchains are expected to be set up by the food industry over the coming years. Eventually, one system will emerge that will be adopted by the whole sector. The likelihood of success depends on whether companies are prepared to be open enough. Data are encrypted, but the openness of blockchains is what makes them so revolutionary. New applications will also emerge that, as with the Internet in the recent past, we are not even able to predict right now (Future Thinkers, 2018). The main themes for blockchain and the consumer industry at present (Parker, 2016) can be classified as follows:

1) Traceability and visibility across the value chain. Increasing speed and flexibility in the supply chain drives the demand for real-time tracking across partners.
2) Fraud and provenance transparency. Customers and watchdogs want to know where goods come from. Safety is the key, and fraud and counterfeit cost reputation.
3) Redundant and incomplete data. Existing data systems are based on messages between silos, with different organizations having different or incomplete data.
4) High friction enterprise integration. Transaction volume and speed of the business lead to a highly disputed environment, erode trust, and expose cash.

The same problems that are hindering integration and standardization of the supply chain are also impairing development of blockchain implementations (UniversaBlockchain, 2017). Two prominent issues have been identified in this respect, namely: confidentiality issues (*e.g.*, companies being resilient to share private information to potential competitors) and technological development —or lack thereof— in upstream suppliers. For blockchain technology to be properly evaluated, proposed solutions should be compared with alternative solutions requiring the same degree of coordination, standardization, transparency and development rather than simply with existing solutions, which are often too easy to compare. Blockchain technology has properties that are desirable for supply chain traceability on a strategic level, and a need exists for researchers and businesses to explore novel ideas on how to harness its capabilities.

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Blockchain technology is bound to change business processes by virtue of its facilitating access to any information about what foods contain, and their origin from farm to table, in seconds, in order to prevent counterfeiting and help the supply chain to meet customers' demands for accuracy, transparency and expeditiousness. Consumers seek confidence in the authenticity of foods, and assurance that food is produced with concern to environmental impact and under ethical working conditions (Loop, 2016; New, 2010). In addition, consumers and other stakeholders hold companies accountable for wrongdoings that may occur outside their own organization (e.g., within their suppliers or end-consumers) (Parmigiani et al., 2011). In response, companies must oversee the entire supply chain involved in a product to avoid misconduct and communicate the ensuing information transparently to their customers. As a result, companies are pressed to improve their ability to trace products all the way from producers to end-consumers. Sophisticated traceability systems can facilitate this task by, for example, responding efficiently to product failure and delivering trustworthy information to all relevant parties.

9. Conclusions

Blockchain technology has been the subject of extensive research lately, but scarcely in connection with supply chain traceability. Although some companies have launched pilot projects using blockchain technology to manage their supply chains (Kharif, 2016; Tian, 2016), no detailed information about the technical implementation of such projects has been reported. In any case, the retail industry has seen potential in using this technology for improved traceability. Thus, in a recent study, English & Nezhadian (2017) claimed that, while some properties of blockchain implementation might be useful towards supply chain management, there are still few uses to support this assertion. With so little research on this subject, it is difficult for industrial stakeholders to understand exactly how blockchain technology could be used in their specific businesses. In order to better understand the technology and, possibly, generate new

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implementations, they would benefit from the development of a universal evaluation model that does not yet exist.

One of the most promising blockchain trends is its growing disruptive presence in the Internet of Things (IoT) (Newman, 2017). Thus, companies are pioneering innovative new solutions that use blockchain technology for tasks such as tracking goods as they move and change hands in the supply chain, monitoring the location and condition of assets such as industrial machinery at remote work sites, or storing medical data. Food adulteration is a steadily growing challenge that requires the use of reliable, robust tools to verify the nature of products throughout the food chain. Blockchains are powerful tools for avoiding food fraud by, for example, assuring geographic and biological origin. A number of strategies for standardizing food authentication issues with blockchain technology have been developed much in the same way as in the healthcare sector (Engelhardt, 2017). The tool of choice in this case depends on whether the particular problem involves

- saving time (e.g., shortening transaction times from days to seconds);
- avoiding costs (e.g., overheads, intermediary costs);
- reducing risks (e.g., tampering, fraud, cybercrime); and
- increasing trust (e.g., through shared processes and record keeping).

Research conducted so far suggest that using blockchain technology can advantageously help to achieve traceability (Aung and Chang, 2014). In addition, blockchain technology allows all stakeholders to check the entire history and current location, for example, of a product. In addition, the technology creates transparency for all participants. In fact, by irreversibly storing data, blockchain technology creates a unique level of credibility that contributes to a more sustainable industry. Information on a blockchain allows companies to strengthen their relationships with current customers and to attract new ones.

Although assuring food traceability with blockchain technology looks promising, there remain some limits to be considered. One is that we are still relying largely on sensors such as RFID tags or barcodes to scan food tracking data, and data collecting sensors are connected to

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the blockchain network. Even though the data stay immutable, the blockchain does not have a verification mechanism to prove whether the raw data were correct. If one tampers with a sensor, the blockchain will have nothing to do with detection. One other issue is that the overall cost of implementing blockchain technology is unpredictable, especially when the existing, highly mature supply chain system has been used for so long. There is also the question as to what kind of data should be publicized. If manufacturers keep their formulas as business secrets, they will have to decide whether to reveal them and, without a clear policy in this respect, they may stand on the wrong side of the trends line (Seibold, 2016).

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848 **Table 1.** Blockchain solutions to traceability problems.

PROBLEM	SOLUTION	REFERENCE
How can one coordinate individual activities over the Internet without secured centralized storage?	Blockchain uses chronological distributed databases where blocks are linked to each other in a proper linear manner and cannot be deleted.	Anderson (1996); Benkler (2006); Nakamoto (2008)
How can one validate entries without a central authority to verify that a transaction is not fraudulent or invalid?	Blockchain uses a probabilistic approach. It forces information travelling over a network of computers to become more transparent and verifiable by using mathematical problems that require substantial computational power to solve.	Scheneier and Kelsey (1998); Nakamoto (2009); Bonneau et al. (2015); Wright and De Filippi (2017).
How can one ensure that only legitimate transactions are recorded into a blockchain?	A new block of data will be appended to the end of the blockchain only after the computers on the network reach consensus as to the validity of the transaction. Consensus within the network can be achieved through different voting mechanisms.	Franco (2014); Bonneau et al. (2015); Wright and De Filippi (2017).
How can one preserve historic records?	When a block has been added to a blockchain, it can no longer be deleted. In addition, the transactions it contains can be accessed and verified by everyone on the network. It becomes a permanent record, which all computers on the network can use to coordinate an action or verify an event.	Bonneau et al. (2015); Wright and De Filippi (2017).

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Table 2. How blockchain technology relates to different trust classes.

Mechanism of influence		**Blockchain characteristic**	**Affected trust**	**Effect on transactions**
General	Transparency	Public–private keys (digital signature)	Authentication trust	Make trust irrelevant
		Immutable transaction history	Resource access trust Delegation trust Provision trust (Trusting beliefs)	Increase trust
	Security	Encryption Decentralization	Infrastructure trust	Increase trust
Case-specific	Restriction	Protocol-governed rules restricting the kind of data that are allowed	Provision trust	Increase trust/Make trust irrelevant

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Table 3. Selected applications of blockchain technology in the agricultural and farming food-supply chain.

Food	Goal	Advantage	Result	References
Fish	Auditable system	Reduce transaction costs and increase transaction capacity	Certifications	Provenance (2015)
Wine	Increase performance, revenue, accountability and security	Most reliable and secure global transactions	Management	Chainvine (2016)
Agri-food	Allow quality and digital identity to be certified	Especially for "bio" and DOCG products	Quality	AgriOpenData (2016)
Agri-food	Trusted information throughout the agri-food supply chain	Guarantee of food safety, by sharing the authentic data in production, processing, warehousing, distribution, etc.	Trust	Tian (2016)
Fruits	Public, immutable, ordered ledger of records	Decreased variance of mining rewards	Fairness	Pass and Shi (2017)
Pork	Brand protection and security through transparency	Enhancing consumer loyalty	Reduced risk	Arc-net (2017)
Large enterprises	Food tracking project	Integration with existing systems used by retailers, wholesalers and food manufacturers	Traceability	IBM (2017)
Fresh food	Enabling data transparency and transfer from farm to fork	Information on product origin including sensor data	Transparency	Ripe (2017)

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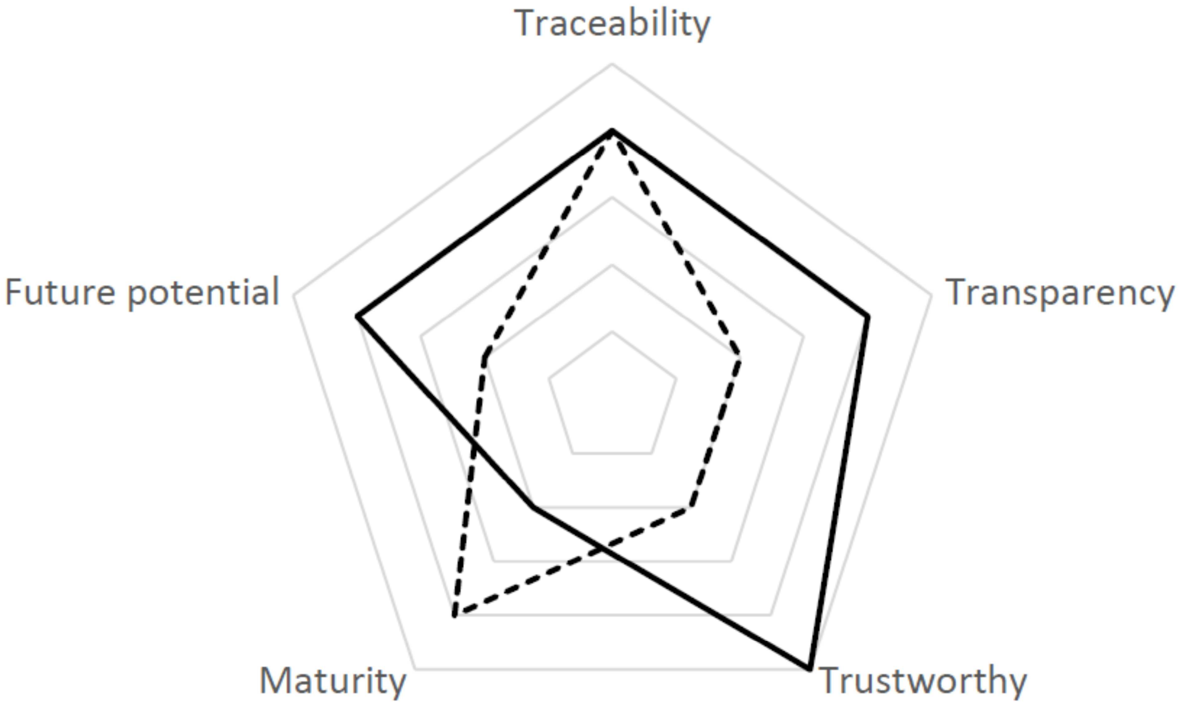

856 **Fig. 1:** Spider chart of a blockchain (solid line) versus a centralized system (broken line).

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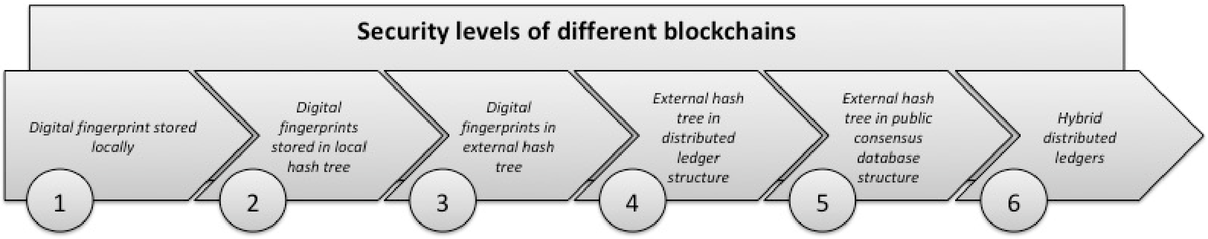
857 

858 **Fig. 2:** Security levels of different blockchains.

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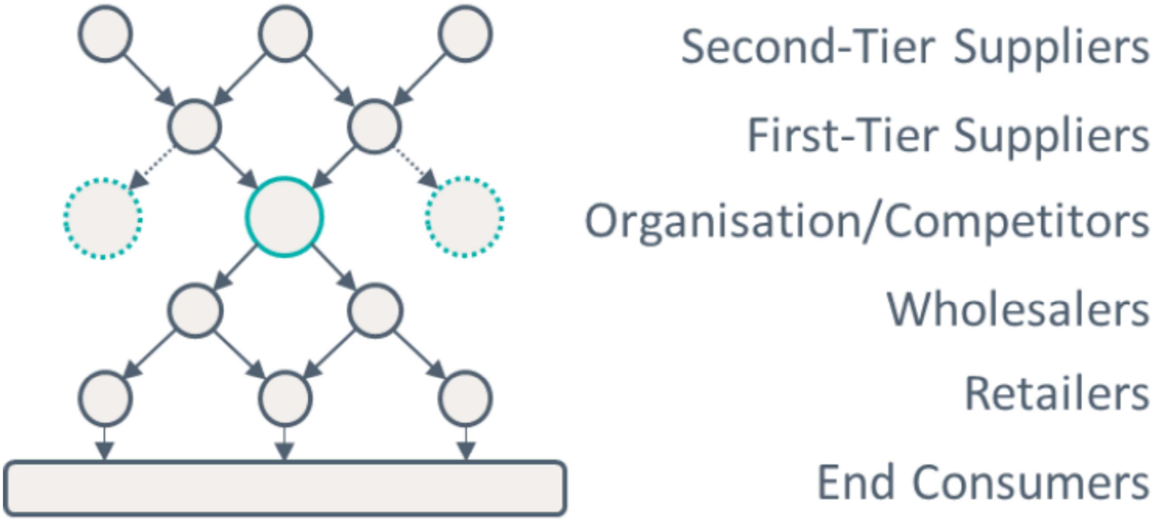
859 

860 **Fig. 3:** A complex supply chain with many stakeholders.

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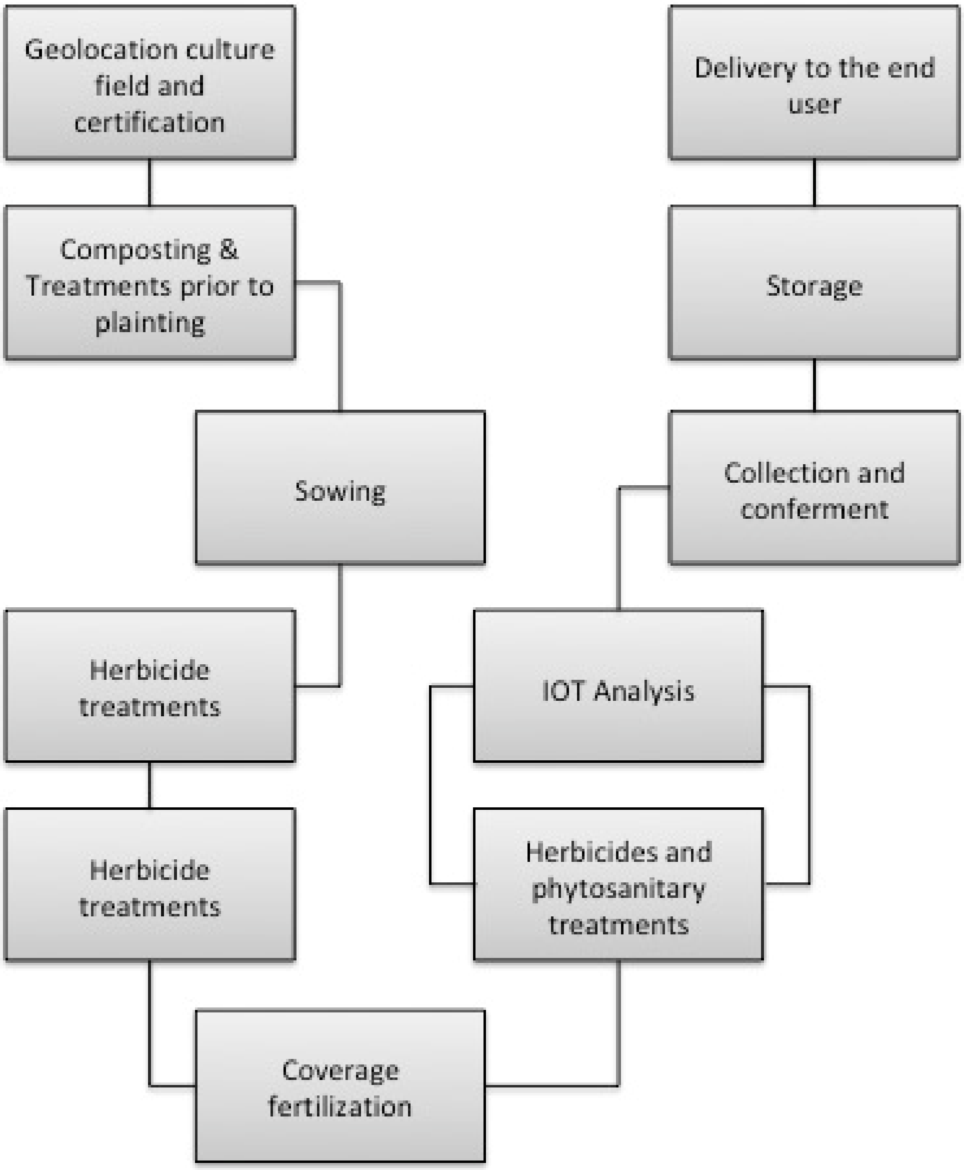

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862 **Fig. 4:** Traceability of agricultural products.

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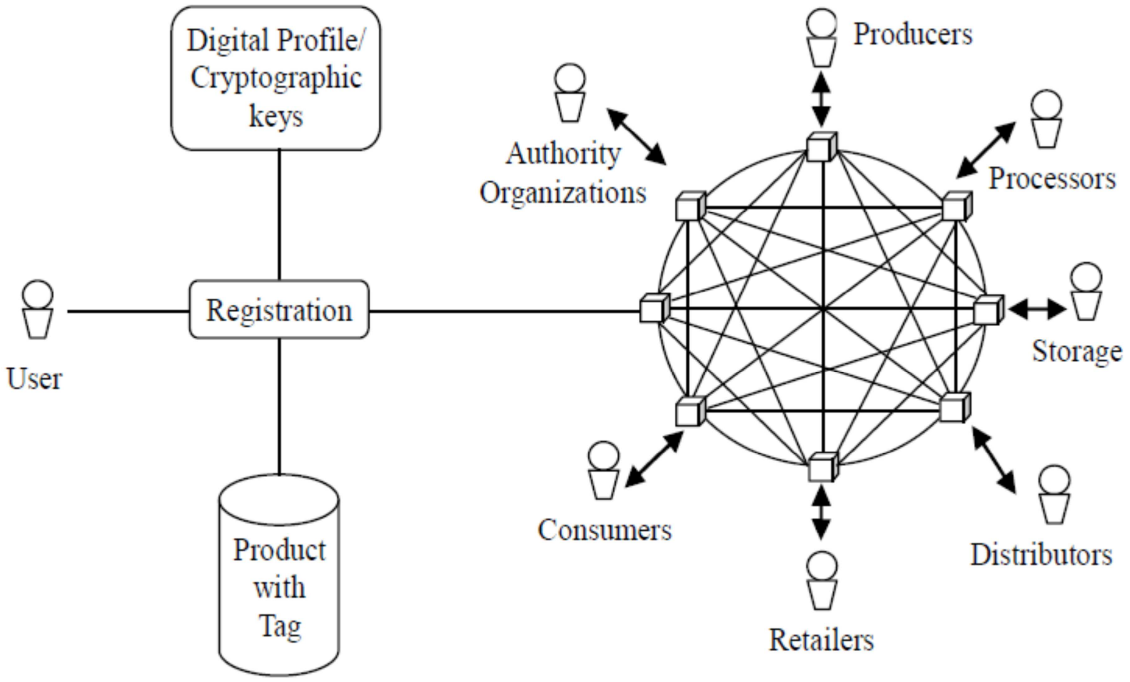

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864 **Fig. 5:** Conceptual framework of the traceability system.

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Research Highlights:

-Tracking and authenticating the food supply chain to understand provenance is critical.

-Solving traceability issues and ensuring transparency can be done by using blockchain.

-Blockchain is growing disruptive in the Internet of Things.

-Research suggest that blockchain technology can help to achieve traceability.

-Blockchain technology looks promising, but there remain some limits to be considered.

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