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Bridging the Gaps in Traceability Systems for Fresh Produce Supply Chains: Overview and Development of an Integrated IoT-Based System

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Abstract: Traceability, namely the ability to access information about a product and its movement across all stages of the supply chain, has been emerged as a key criterion of a product's quality and safety. Managing fresh products, such as fruits and vegetables, is a particularly complicated task, since they are perishable with short shelf lives and are vulnerable to environmental conditions. This makes traceability of fresh produce very significant. The present study provides a brief overview of the relative literature on fresh produce traceability systems. It was concluded that the commercially available traceability systems usually neither cover the entire length of the supply chain nor rely on open and transparent interoperability standards. Therefore, a user-friendly open access traceability system is proposed for the development of an integrated solution for traceability and agro-logistics of fresh products, focusing on interoperability and data sharing. Various Internet of Things technologies are incorporated and connected to the web, while an android-based platform enables the monitoring of the quality of fruits and vegetables throughout the whole agri-food supply chain, starting from the field level to the consumer and back to the field. The applicability of the system, named AgroTRACE, is further extended to waste management, which constitutes an important aspect of a circular economy.

Keywords: traceability; food safety; IoT; event capturing; integrated information system; information management; transaction support; data sharing; real-time communication; interoperability

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1. Introduction

1.1. General Context of Traceability for Agri-Food Supply Chains

Maximizing food safety throughout the entire supply chain is of great importance and constitutes a major challenge towards the development of reliable agri-food supply chains. Focusing on fresh produce supply chains, they deal with perishable commodities, such as fruits and vegetables, which continue to respire and metabolize after harvest [1]. As a consequence, the management of fresh food tends to be more complicated and costly compared to any other supply chain. This is mainly because of the products' short shelf lives and sensitivity to temperature and humidity as well as possible damage during harvesting, transportation, processing, packaging or handling and shipping [2,3]. In essence, the longer the time period pertaining to the different phases within the supply chain, the larger the probability of the food quality to get deteriorated. A number of stages take place until the fresh food is supplied to the consumers. According to Bosona and Gebresenbet [4], who reviewed the literature on food traceability, the initial stage includes in-field activities, ranging roughly from seeding or planting and harvesting to transportation and delivery to the food processing industry. There, various operations are carried out such as cleaning, chemical treating, packaging and delivery to distributors. Subsequently, perishable products need additional maintenance, which is vital for the purpose of delivering, to the customers, products of great quality. This implies the need for appropriately cooling the storage as well as modified atmosphere storage facilities and transportation means.

Furthermore, a wide range of routines must be followed at each phase of the food life cycle so as to contain foodborne pathogens. These pathogens refer to a broad spectrum of bacteria, viruses, parasites and chemical substances that can affect food quality. Remarkably, the number of incidence corresponding to foodborne pathogens is alarmingly increasing worldwide, thus, putting at risk the health of people and contributing to the global burden of mortality according to the World Health Organization (WHO) [5]. For instance, as reported by the Centers for Disease Control [6], the incidence of infections owing to *Salmonella*, *Shigella* and *Listeria* has remained unchanged in the U.S. In addition, a plethora of cases have been reported during the last twenty years, such as the Chinese milk and tainted pork scandals, horse meat scandal in Europe, the Australian rockmelon and U.S. Hami melon listeriosis outbreaks, to mention but a few [7–11].

For the sake of assuring food safety, the governments in cooperation with health organizations have strengthened management strategies targeting at traceability of fresh produce supply chains through issuing relevant regulations and laws. Indicatively, the General Food Law in the European Union [12] and the Food Safety Law of China [13] require the food producers to ensure food traceability with the aim of recalling products in a timely manner and providing useful information to consumers. Consequently, traceability has become a prerequisite challenge to be addressed by all food-related stakeholders towards an optimal quality management of the fresh produce supply chain. Traceability information can offer the possibility to enterprises for discount planning, stock rotation, sales tracking, inventory ordering and warning customers about the suspect products [14]. In turn, reliable traceability systems build customers' trust on the traceable food products, leading them to be willing to pay more for such products [15].

In spite of the numerous studies that have been published in the relative literature concerning the traceability of agri-food supply chains [16–20], there was no common and clear definition of food traceability. By reviewing the relevant papers in this field, Islam and Cullen [14] recently proposed a concise definition of food traceability:

> *"Food traceability is 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"*

For the creation of the above definition, the main drivers (the motivating factors), beneficiaries (referring to who benefit from the food traceability systems), typologies (e.g., "forward" and "backward" traceability) and principles (describing how traceability can be efficiently implemented) were taken into account. The term "specific information" exists in the aforementioned definition to denote that complete traceability is never possible, owing to the large volume of information and the required cost. Moreover, the term "access" signifies the capability to view, get or exploit the recorded information and the "identification" to highlight the process of assigning to the product distinctive codes. Finally, the term "captured" is used to demonstrate product's information collection, while the term "integrated" expresses the integration of linking, merging, sharing and transmission of the recorded data [14].

As far as the traceability of fresh produce supply chains is concerned, it involves internal and external entities. The "internal" entities refer to enterprises engaging in production, processing, cold chain logistics, sales enterprises, etc. In contrast, the "external" ones deal with consumers and regulatory agencies [21,22]. Additionally, the fresh produce supply chain contains long production chains, several production and sales points and extends to a large area. Hence, both supervision and tracing are exceptionally challenging in practice.

1.2. Incorporating Internet of Things to Optimize Agricultural Traceability Systems

A large amount of data have to be gathered across the supply chain for traceability purposes. Early traceability systems used to rely on records kept by workers on the field and then manually entered in paper or computer-based systems. As a result, faulty information recording could be made. Following the rapid technological advancements associated with agriculture 4.0 [23,24], especially with Internet of Things (IoTs) and machine learning [25–28], more efficient and trustworthy gathering procedures have been utilized. Various sensor technologies, incorporated to IoT systems, support technologies involved in each stage of the food supply chain, hence, providing a more effective way for the purpose of recording and exchanging useful information. These technologies include, for example, barcodes, Radio-Frequency IDentification (RFID), Quick Response (QR) codes and Wireless Sensor Networks (WSN) [29,30].

Regarding a QR code, it is a label that can be read, by a scanning device, a mobile phone for instance, and is made of a white background along with black squares arranged inside it. Although QR codes are similar in practice with barcodes, they encompass more information, since they can store information both vertically and horizontally; in contrast, barcodes contain only horizontal information. Hence, QR codes have a considerably higher capability of providing information, making them very popular in food industry. Furthermore, tagging food items with RFID enables the user to identify and track inventory problems as well as provide details on the overall performance of agri-food supply chain by emitting radio waves and receiving back signals from the tag [31]. RFID technology also offers real-time location tracking, condition monitoring, warehouse automation and transaction monitoring services. Compared with barcodes, RFID outperforms due to its capability to transmit precise information of high capacity with higher speed. Nevertheless, the foremost drawback in this technology is its relatively high implementation cost [2,32]. As for WSNs, they refer to a variety of spatially distributed sensors with the intention of monitoring and recording the environmental conditions, including temperature, humidity, wind and pressure, by applying certain protocols and standards [33]. The low-power, small-sized, multipurpose and self-organized nodes are a scalable and cost-effective technology supporting WSN [34], rendering them essential tools towards automation of agricultural practices and enabling effective traceability.

Various communication approaches can be implemented in traceability systems, depending on the degree of technology and standardization. According to [14], there are three indicative examples of communication approaches; (a) the "One up-one down" approach, that stores information concerning suppliers and customers, (b) the "Pedigree" approach according to which the product's history from all the previous process nodes is available, and (c) the "Centralized" approach, where a cloud-based centralized database exists that is managed by a third party. However, the centralized database is prone to get manipulated by enterprises [35]. In pursuance of increasing the reliability and security of information transmission between various stakeholders, blockchain has emerged, which can be simply defined as "*a distributed ledger maintaining a continuously growing list of data records that are confirmed by all of the participating nodes*" [36]. In practice, blockchain is a kind of decentralized tamper-proof database, which can be accessed by many parties, while any action must be consistent with agreed rules. Blockchain makes use of a cryptographic algorithm as a means of generating a chain comprising of data blocks in chronological order. A block is a record enclosing data along with information from the previous block's hash, which results in a value representing its own unique hash [37]. The hash, in turn, corresponds to the digital "fingerprint" of a wide range of block's data; one of the key principles of the blockchain architecture. If any tampering with the data takes place, this digital fingerprint alters leading to an invalid chain [29].

In summary, food supply chains have been evolved over the years aiming at offering improved services at a lower cost. Figure 1 depicts a simplified food supply chain consisting of its main stages/links. In IoT-based supply chain paradigms for traceability purposes the activities, carried out within each stage, are recorded in the corresponding block, as described above. Moreover, the information in relation to the transactions is verified by the food supply network business partners and, subsequently, added in the blockchain forming an immutable record [38]. Based on the tracing direction, the product can be either tracked top-down throughout the food supply chain (forward traceability) or traced bottom-up (backward traceability). Both forward and backward traceability are regarded to be important components of any food traceability system [4,39]. Finally, traceability systems should have to cope with a variety of concerns regarding food security, fraud and withdrawal as well as societal issues, compliance with regulations and consumers' awareness [40].

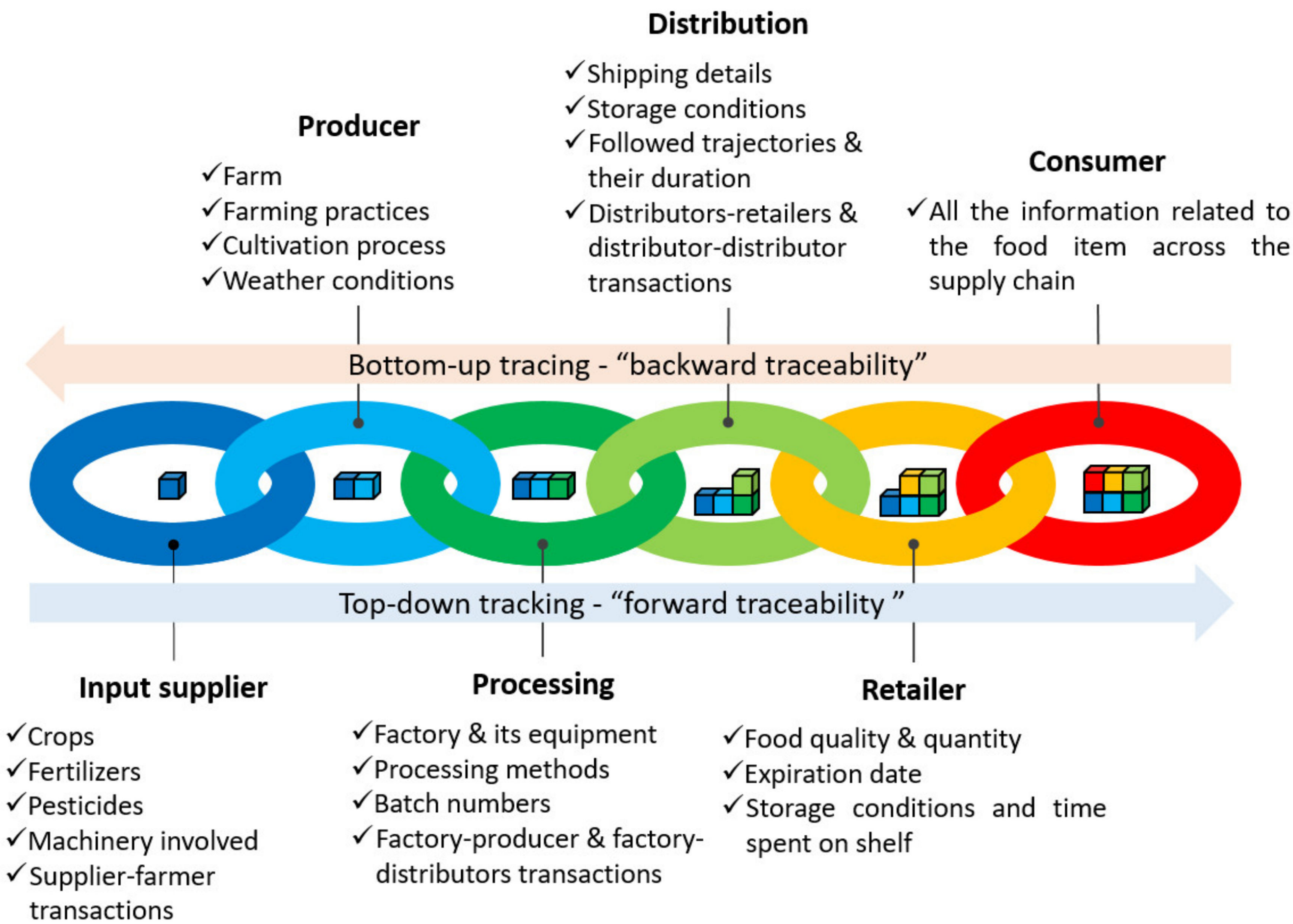

Figure 1. An illustrative example of a fresh produce supply chain along with the information recorded in each stage within a block; products flow forward the food supply chain, while both forward and backward traceability can take place following the product in either top-down or bottom-up direction across the food supply chain, respectively.

1.3. Related Work

Taking into account the significance of the development of flexible and reliable agri-food traceability systems, several efforts have been presented in the scholarly literature in this direction. In brief, focusing on the recent literature for agri-food supply chains, indicative studies (without applying blockchain technology) include application of QR codes [41–43], RFID tags [44,45], and also combination of QR codes with RFID technology [46,47]. In [41], a traceability model was proposed for vegetables that utilizes QR codes as information carriers for identifying various aspects associated with cultivation, storage, processing and transportation, while web Service technology was used for exchanging information. Similarly, QR codes were applied in [42] and [43] for tracing a farm-to-fork supply chain regarding vegetables and melons, respectively. In [44], RFID tags on products of a fruit warehouse and personal digital assistant devices were implemented. This semi-automatic traceability platform resulted in shorter time required as regards data analysis and management. In the same vein, Hsu et al. [45] used an RFID-based traceability system pertaining to live fish supply chain leading to valuable results for practical reference. RFID tags were also proposed in [46] in conjunction with QR codes for the design of a traceability system for wheat flour mills. QR codes were implemented to identify small packages of wheat flour, while RFID tags were used to record logistics information. This proposed system proved to be more efficient in terms of information queries than a system purely based on paper records. Both QR and RFID technologies were also implemented in [47] for tracing a prepackaged food supply chain together with XML to facilitate the sharing of information among different stakeholders.

With the ledger technologies, such as blockchain, being more and more streamlined, several studies proposing cloud traceability systems started to gain ground [48,49]. Cloud technologies can contribute to better real-time identifying, locating and tracking the status of products. This can facilitate the retrieval of useful data, analytics, storage and connectivity throughout the supply chain, which are significant aspects when it comes to traceability of perishable products so as to assure the required safety standards [50]. In short, Mao et al. [48] proposed a Food Trading System with COnsortium blockchaiN (FTSCON) so as to increase security and trust in transactions. Their results demonstrated that the proposed system can enhance merchants' profit. Finally, Leng et al. [49] developed a blockchain focusing on supply chain system of agricultural products relying on a double chain architecture; a "user information chain" and a "transaction chain". This architecture proved to have the potential to considerably improve the trustworthiness of the platform and also the overall system's efficiency. More information about the implementation of blockchain for facilitating different functions of agricultural traceability systems can be found in recent review studies such as [29,51–53].

In spite of the increasing interest in traceability systems regarding fresh produce, the available integrated IoT-based systems are scarce and at a relatively early stage of development. These efforts, that are available on the market, include solutions covering the supply chain from field to retailer, namely GR-LIVE (Food Logistics; Waukesha, WI, USA) [54] and FoodLogiQ's Track + Trace (LogiQ; Charlotte, NC, USA) [55], from the packaging plant to retailer, namely iApp (ORBCOMM; Rochelle Park, NJ, USA) [56] and AutoSense (Emerson; St. Louis, MO, USA) [57], and from the packaging plant to consumer, namely HarvestMark (iFooDS and HarvestMark; Seattle, WA, USA) [58] and iris (Frequentz; San Ramon, CA, USA) [59]. A general remark for these systems is that they deal with limited parts of the supply chain and do not cover the entire range of it, i.e. from field to consumer, while they do not provide an open architecture.

1.4. Aim of the Present Study

From the literature analysis presented above, several traceability systems have been developed and are commercially available. However, significant gaps in the literature were identified; the short range of application of these systems, which cover only a few stages of the supply chain, the extremely limited interoperability among the different systems, and the closed structure not allowing for open source use. In this study, a state-of-the-art IoT-based system is proposed, named "AgroTRACE", aiming at providing an integrated solution for traceability and agro-logistics of fresh fruits and vegetables from farm to fork and back to the farm by also tracing waste to be used as input for crop production. Furthermore, AgroTRACE is an open source system, composed of a web platform available for all the participants of the food supply chain. In addition, a user-friendly Android application has been developed for consumers encompassing all the basic functions in relation to the on-the-fly scanning and retrieving of all the important aspects of the perishable products. The system, which is implemented within the AgroTRACE project [60], supports both the internal and external traceability throughout the supply chain.

Table 1 presents a comparison of the proposed system with the aforementioned traceability systems currently available on the market. It can be inferred that the proposed modular structure is based on open and transparent interoperability standards that allow for faster monitoring of the system's operation in product's tracking processes. As a consequence, the quality of the fresh produce is guaranteed via a reliable traceability system, which starts from the farm level up to the consumer and back to the farm, in contrast with the limited range of the supply chain of the other available systems. Moreover, AgroTRACE incorporates all of best data transfer technologies used by other systems, namely RFID, LoRaWAN network for inter-device communication, and beacons technology along with the corresponding Bluetooth Low Energy (BLE) communication protocols. The innovation of AgroTRACE is further reinforced by covering also the part of waste management and recycling, incorporating circular economy practices to the traceability system. To this end, the proposed solution fully supports traceability of biowaste by providing documentation on supply chain partners' Corporate Social Responsibility and supporting industrial symbiosis. The latter refers to the process where the "waste" of a production process is an input of another unit. To sum up, the proposed holistic approach is the first that uses an open architecture, deals with waste management, covers the entire length of the supply chain, combines a variety of IoT technologies for real time acquisition of information and decision making and considerably facilitates interoperability.

Table 1. Comparison of the available IoT-based traceability systems on the market with the proposed solution (AgroTRACE).

IoT System	GS1 Standard	Supply Chain Range	Minimum Reference Level	Data Transfer	Modular Structure	Waste Treatment	Open Access
GR-LIVE	x	Field-Retailer	Product	RFID [1]	√	x	x
iApp	x	Packaging plant-Retailer	Container	RFID, Satellite, BLE [2]	√	x	x
AutoSense	x	Packaging plant-Retailer	Container	RFID, GSM [3], NFC [4],	√	x	x
Harvest Mark	x	Packaging plant-Consumer	Product	RFID	x	x	x
FoodLogiQ's	√	Field-Retailer	Product	x	x	x	x
iris	√	Packaging plant-Consumer	Product	x	√	x	x
AgroTrace	√	Field-Consumer-Field	Product	RFID, LoRaWAN, BLE	√	√	√

[1] RFID: Radio-Frequency IDentification; [2] BLE: Bluetooth Low Energy; [3] GSM: Global System for Mobile communications; [4] NFC: Near Field Communication.

2. Conceptual Framework of AgroTRACE

The proposed system traces the supply chain via a process consisting of four stages, namely recognition, recording, evaluation and sharing, which are described in the following subsections.

2.1. Recognition

Recognition refers to the capability offered by AgroTRACE to distinguish the fresh products, the infrastructure and sites, from the producer to the consumer, by taking into account the GS1 standards. In particular, the following standardization is incorporated:

- Global Location Number (GLN): Distinction among the locations of farms, packaging units, wholesalers, distributors, retailers, etc.
- Global Trade Item Number (GTIN): Identifying trade items by providing a single number for each product.
- Electronic Product Code (EPC): Providing serial numbers for the commercial item.
- Serial Shipping Container Code (SSCC): Providing containers' serial codes for the pallets.
- Global Returnable Asset Identifier (GRAI): Distinction of the returned produce.

2.2. Recording

The carriers pertaining to GS1 system data are utilized for the sake of data management in order to address the needs of the supply chain process for a variety of products. Specifically:

- At retail stores, the EAN/UPC barcodes are implemented for scanning.
- In the interest of identifying the product's units on the pallets and packaging for monitoring products' movement and acquiring information about them across the supply chain, the GS1-128 barcodes are employed.
- GS1 DataBar barcodes are also used, which can provide the same or more information and in less space comparing to UPC barcodes.
- UPC barcodes are used for small-sized products and for products that are difficult to track.
- RFID tags are used which are connected with the products' EPC.
- The data, which are coded in data carriers of the GS1 system, are able to identify the products and enable trading partners to share a great amount of data including the number of batch, the date of production and packaging information, to mention but a few.

2.3. Evaluation

Evaluation refers to the assessment of the gathered information in respect to the goals that can be expressed as Key Performance Indicators (KPIs) which are set by the partners of the supply chain throughout the supply chain. Moreover, the system provides the capability of using KPIs from the Supply Chain Operations Reference (SCOR) [61]. Consequently, anonymous evaluation can be accomplished regarding the chain's partners' performance.

2.4. Sharing

One of the key challenges of the existing traceability systems is their interoperability and data sharing, as they both allow for smooth information exchange when it comes to trade transactions. Towards this direction, the GS1 interface standards listed below are used:

- Global Data Synchronization Network (GDSN): It links the trading partners with GS1 Global Registry through GS1 certified data. This provides the capability of instant electronic exchange of updated, standardized and verified information. Furthermore, the useful information can be shared pertaining to GTINs; unique identity for the owner's product, description of the product, and classification of the product in terms of Global Product Classification (GPC).
- Electronic Data Interchange (EDI): It enables the exchange of important documents between enterprises via a standard format. It can also allow for sharing information including GTIN, GLN and SSCC, which were briefly described above, as well as invoicing, delivery information, order details and payment tracking.
- Electronic Product Code Information Services (EPCIS): It is the standard for the information exchanging dealing with critical events about the monitoring of the route of a product taking place along the agri-food supply chain. It also shares information such as the date, time and location in the action stream of the event of interest, GTIN and GLN.

The framework of the AgroTRACE system described above, along with the implemented standardization throughout the agri-food supply chain, is illustrated in Figure 2. The implementation of GS1 standards is an essential aspect of AgroTRACE system for the purpose of being fully modular and able to receive and send information by utilizing IoT technologies and event capturing applications (e.g., QR, RFID and Barcode readers). As can be inferred from this graph, the ability for traceability is extended beyond the farm-to-shelf route covering also the recycling and industrial symbiosis; the waste of a production process becomes an input for another unit. This realization takes place in the framework of the circular economy context. In this context, the proposed integrated system enables traceability of organic waste by providing the required documentation about the Corporate Social Responsibility to the supply chain partners.

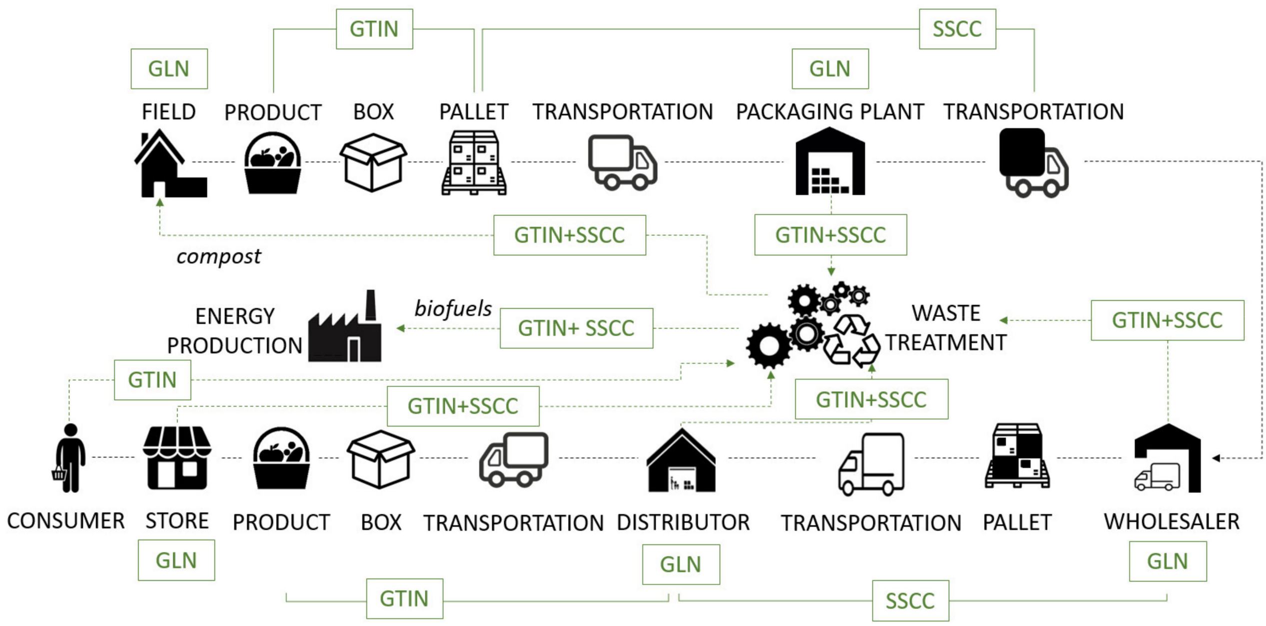

Figure 2. Schematic illustration of the conceptual framework of the AgroTRACE system.

An important strength of AgroTRACE is both the big data collection and management in real conditions covering various stages of the supply chain from farm-to-shelf-to-farm. As far as big data management is concerned, the open source Apache Hadoop software [62] is used that enables distributed processing of big data in computer clusters by utilizing relatively simple programming models. This software has been created as a means of scaling up from single servers to a plethora of machines, each one providing localized computation and storage. Rather than depending on hardware for offering high availability, the library has been designed to find out and address failures on the application layer. The Apache Hadoop project includes the following modules [62]: (a) "Hadoop Common" providing the common utilities which support the other modules, (b) "Hadoop Distributed File System", which is a distributed file system offering accessibility to application data, (c) "Hadoop YARN", offering a system for cluster resource management and job scheduling, (d) "Hadoop MapReduce" enabling parallel processing when it comes to large data sets, and (e) "Hadoop Ozone", which is a scalable and distributed object store for Hadoop. Moreover, applications utilizing frameworks, such as Apache Spark (an engine enabling large-scale data processing), Apache Hive (a software facilitating the management of large datasets being in distributed storage by using Structured Query Language (SQL)) and Apache YARN (briefly analyzed above), can operate natively without any alterations. For the implementation of the Apache Hadoop software, the open source software Apache Storm [63] and Apache Mesos [64] are also used because they enable reliable real-time processing of streams of data and they also allow elastic distributed systems to be easily developed and run efficiently.

3. The AgroTRACE Infrastructure

Throughout the design and implementation of the AgroTRACE system, full compliance with GS1 standards and best practices related to them are ensured. The range of the tracing extends from the field to the consumer and back to the field by also monitoring waste treatment. Moreover, the modular structure offers flexibility and adaptability, while the use of open standards favors the interoperability and data sharing. Interoperability is one of the greatest challenges in the development of an integrated IoT system in agriculture [65]. The proposed system includes integrated information management based on a System-of-Systems (SoS) approach. This approach supports interconnection and interoperability of individual sensing systems in a single system that provides access to the user for the implementation of different traceability scenarios. It also allows existing information systems to continue to operate, by receiving data from partner systems.

As can be depicted in Figure 3, AgroTRACE consists of three main elements: (i) the event capturing and IoT application platform, (ii) the transaction support and information management system and (iii) the data mapping system.

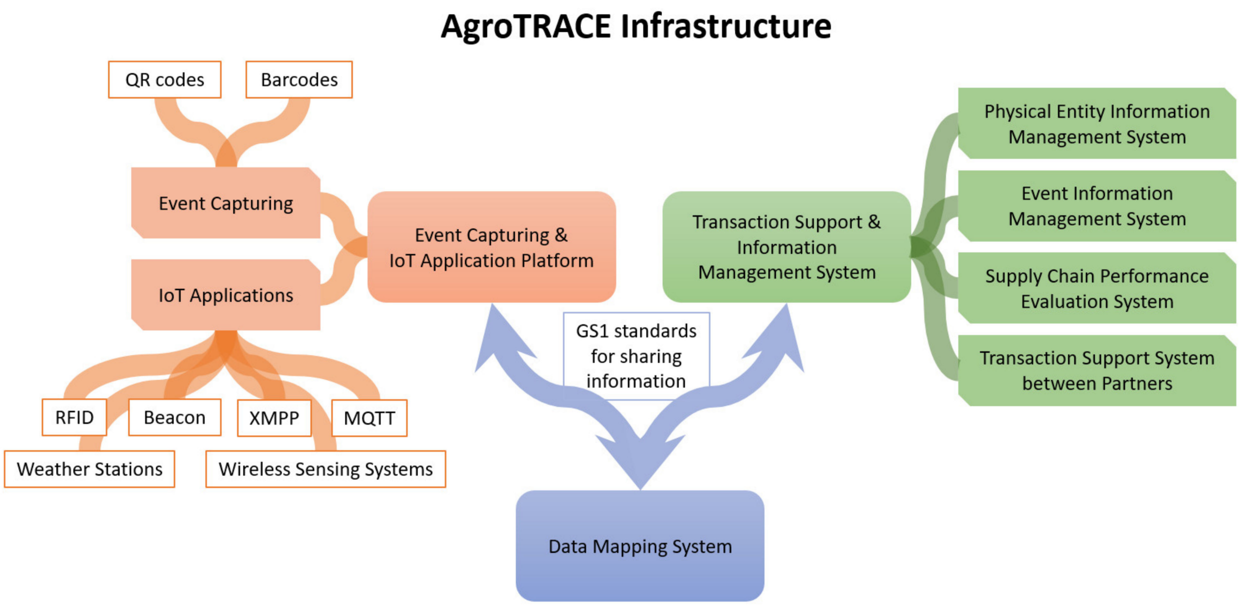

Figure 3. Simplified graph of the infrastructure of AgroTRACE system showing its main three elements and the involved IoTs.

3.1. Event Capturing and IoT Application Platform

This platform is the location, where the gathering, storage and processing of the data originated from different event capturing applications, IoT applications and networks as well as third-party applications take place. More specifically, in the framework of AgroTRACE, two indicative event capturing and five IoT applications have been developed, which are linked together for supporting particular use cases. The context of these applications is briefly described below.

3.1.1. Event Capturing Applications

The event capturing applications deal with visual reading by utilizing smart devices for:

- Monitoring the route from the field to the packaging plant (see also Figure 2). During harvest, the numbers of the perishable products, i.e., vegetables and fruits, are scanned via the GRAI application and imprinted in barcodes or QR codes on pallets.

The same batch numbers are scanned during entering the packaging plant and, in particular, at the sorting line and at the temporary storage point. These numbers are linked to the corresponding field's and packing GLN numbers as well as through the sorting line systems by using the GTIN numbers of the available products and SSCC numbers of the pallets. Concerning the former, the extended form, namely GTIN-128, is used which contains information of different batches.

- Management purposes in the retail point. The customer is able to scan the number of the fresh product by using the GTIN-128 application. The numbers are imprinted in QR codes or data bars, thus allowing for access to its history. Thus, the product can be tracked after the shelf of store, until the refrigerator of the consumer.

3.1.2. IoT Applications

In fresh produce traceability systems, there is the need for continuous monitoring of the location and conditions of a product throughout the supply chain from farm to store. Starting from the in-field crop production management practices, the need for informed decisions on fertilization, plant protection, harvesting, transport, storage and standardization has led to the development and deployment of IOT in agriculture. Such wireless sensing systems allow for measuring crop, soil, weather and environmental parameters as can be seen in Table 2. In short, the sensing systems of AgroTRACE can be classified into systems implemented at farms and during transportation and storage. In practice, weather stations and wireless sensing systems are used at farm level for measuring weather parameters, including ambient temperature, relative humidity, atmospheric pressure, wind velocity and precipitation. Furthermore, important soil parameters are measured, such as soil temperature, moisture content and electrical conductivity. Finally, greenhouse gas emissions are measured at points of interest, while tracking tractors' activity is accomplished through Global Navigation Satellite System (GNSS). Checking the conditions of transport and storage of vulnerable products and tracking their location is also of major importance. For this purpose, measurements of temperature, humidity and CO_2 concentration are continuously taking place.

Table 2. The main parameters measured by IoT systems across the agri-food supply chain.

Supply Chain Part	Parameter Type	Measured Parameter
Farm	Weather	Ambient temperature Relative humidity Atmospheric pressure Wind velocity Precipitation
	Soil	Soil temperature Moisture content Electrical conductivity
	Environment	Greenhouse gas emissions
	Location	Tractor's location tracking
Transportation and storage	Transportation and storage environment conditions	Ambient temperature Relative humidity CO_2 concentration

The IoT applications include also the use of RFID technology at several stages of the fresh produce supply chain ranging from the field level to the store and also to waste management. In particular, the following five cases of using RFID take place:

- From field to the packaging plant: Each pallet leaves from the field having an RFID with an EPC number. In the packaging plant, RFID readers are used to scan each batch at the sorting lines and the temporary storage sites, where the products are pending sorting and packaging. Regarding the EPC numbers, they are linked to new EPC numbers to be assigned to different batches and pallets by using sorting systems.

- In the packaging plant: Each package (at the level of cardboard box or the corresponding reusable packaging item) and each pallet have an RFID tag with EPC number, while the packaging plant has RFID readers at the exits of the products to be sent.
- During transportation: The trucks are equipped with both RFID readers and beacon devices for recording useful data pertaining to humidity, ethylene concentration and temperature, as a means of continuously monitoring the transportation conditions. To this end, the LoRaWAN network is also used for data transmission at the level of city-logistics for enabling prompt response of the supply chain as the fresh commodities approach the retail point.
- In the store: The retail stores are equipped with beacon devices providing useful information to the customer's smartphone via reading EPC numbers with RFID readers.
- During waste management process: Each partner of the supply chain that produce organic waste has to assure the correspondence of each departing pallet with an EPC number on an RFID tag. Waste treatment points are equipped with RFID readers at the entry points undertaking the continuation of traceability at the by-products' production level (biofuels, compost, etc.). As an alternative solution, special brown organic waste bins can be installed in accordance with international standards. The brown bins, which will be marked with RFID, are weighed and identified via intelligent waste management systems (Waste Logistics) in garbage trucks. The information waste quantity is also integrated in the AgroTRACE System. For the above applications, the necessary Application Programming Interfaces (APIs) have been developed that are connected to the middle-tier of the information management platform. They are also connected to the middle-tier APIs of Google Maps and Google Surveys for evaluating several stages of the supply chain, with the intention of integrating the functions of the applications in the use cases.

3.2. Transaction Support and Information Management System

Four subsystems make up the transaction support and information management system which exploits the information given by the aforementioned element of AgroTRACE for tracking the procedures:

- A system for physical entity information management, which, via special queries, enables users to access information, thus, fully leveraging the capabilities for data visualization.
- A system for event information management, which allows users to track events that take place at different phases of the supply chain within clearly defined flows by fully exploiting the data visualization capabilities.
- A system for evaluating the performance of the supply chain, by making a comparison between real-time data and targets that have been set (KPIs).
- A system for supporting the transaction among partners across the entire supply chain by taking advantage of data and information.

3.3. Data Mapping System

The information, which is produced in the platform and the above four subsystems, is standardized via GS1 standards, with the aim of sharing information with other systems. Hence, the information can act as reference knowledge (benchmarking) via its extensive dissemination (knowledge diffusion).

3.4. Standards Followed by the IoT Applications Focused on Information Management

Finally, as far as the IoT applications are concerned, specific standards are followed for the information management, namely:

- Message Queuing Telemetry Transport (MQTT): This lightweight standard messaging protocol allows for both recording and publishing of messages with considerably small volume of data, while it is very useful for connections to remote sites with a small code footprint as well as minimal network bandwidth [66].

- Extensible Messaging and Presence Protocol (XMPP): Based on its abbreviation, going from "P" back to "X", XMPP is a "Protocol" allowing systems to communicate to each other; "Presence" shows the state of an XMPP entity (online, offline or busy); the "Messaging" refers to the part that clients can see; XMPP is designed so as to be "eXtensible", namely able to grow and accommodate alterations. In other words, XMPP is a set of open protocols for real-time communication, which supports a variety of applications, including content sharing, instant messaging, voice and video calling, presence and collaboration [67].

3.5. IoT Communication

Concerning the communication between the devices, a LoRaWAN network is used, which covers a wide range (up to 20 km signal transmission) and demonstrates very low energy consumption. An additional advantage of LoRaWAN network is the zero operating cost of information transmission, since it does not demand that mobile, fixed or satellite telephone networks are used. Regarding AgroTRACE, the network of IoT devices interconnected in a LoRa environment, depicted in Figure 4, consists of the following elements:

- IoT information system supporting data management (cloud), data record and information display.
- Web application and mobile application informing users about the measurements.
- LoRa nodes for recording information and transmit it at the LoRa gate at a distance of up to 20 km.
- Autonomous node systems with solar panels (where required).
- LoRa nodes with sensors in fields and other points of interest, e.g., warehouses and packaging plants.
- LoRa nodes at tractors.
- LoRa nodes for the transported containers.
- LoRa gateway for receiving signals from LoRa nodes and sending them to the information system.
- An IoT platform, through which data are collected and sent to other servers and apps.

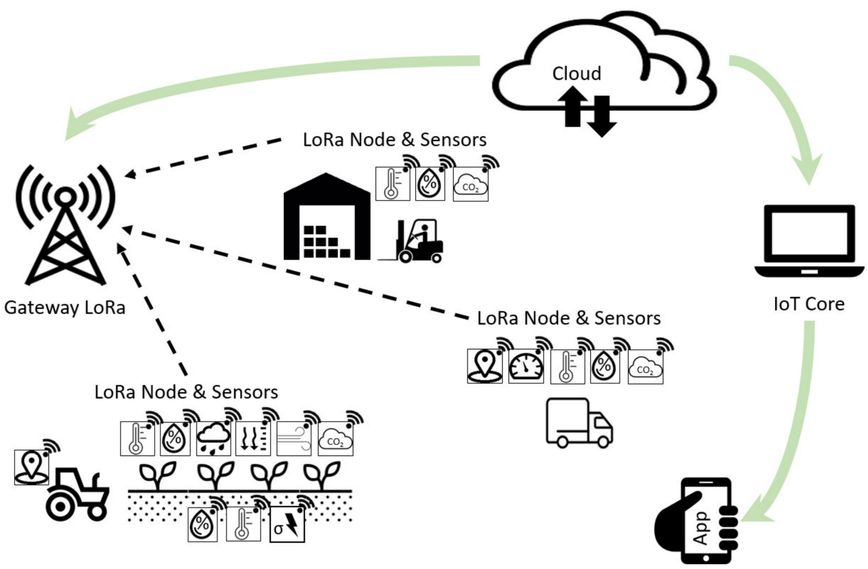

Figure 4. Schematic of IoT implementation using LoRa network.

4. Discussion and Main Conclusions

In the first part of this study, an overview of the traceability systems for fresh produce supply chains was presented. This field is particularly challenging, since fresh produce has short shelf lives and is vulnerable to environmental conditions. For the purpose of securing food safety, traceability has become a consumer driven demand in modern agriculture. In essence, traceability enables consumers to track back the fresh products to the whole supply chain providing useful information concerning the transportation, handling, processing and the packaging reaching up to the producer level. Taking into account the recent developments of sensing technologies and IoT systems, an opportunity is given to trace the fresh produce further, reaching the field level, providing information in relation to the growing conditions and practices and much more. Moreover, traceability provides the possibility to companies for sales tracking and discount planning, as well as tracing batch input materials and recalling across the supply chain, thus, improving their competitiveness. However, owing to the complexity of fresh produce traceability, a large volume of reliable data has to be collected, while information management, interoperability and data sharing constitute key challenges to be addressed. Towards that direction, IoT systems have been incorporated in traceability systems ranging from sensors for gathering important information to RFID, QR codes, WSN and cloud technologies.

Despite the increasing interest in traceability systems worldwide and the advance in IoT technologies, the available traceability systems on market are relatively scarce. Besides, they usually cover a limited part of the supply chain and do not rely on open interoperability standards. In contrast, the AgroTRACE system, proposed in this study, offers a solution for fresh produce traceability based on a modular approach that uses open and transparent standards enabling interoperability. The innovative approach relies on the integration of three elements, namely the event capturing and IoT application platform, the transaction support and information management system, and the data mapping system. Moreover, traceability capabilities go beyond the farm-to-shelf route and cover the farm-to-shelf-to-farm route as well as waste management. For the realization of the smooth operation of AgroTRACE traceability system, a plethora of Information and Communications Technologies (ICT) are used: e.g., visual reading through smart devices (RFID and beacon technologies), MQTT and XMPP protocols for supporting real-time communication even at remote locations, a LoRaWAN network for inter-device communication, and GS1 interface standards (GDSN, EDI, GTIN, GLN, SSCC and EPCIS) for interoperability and data sharing.

In a nutshell, traceability has become a perquisite of improving food quality and safety, recall efficiency, information transparency, security and trust in transactions. However, many challenges need to be overcome. In this context, the proposed AgroTRACE traceability system, by following a novel system architecture and utilizing the most recent technological advances, can contribute to more efficient operation of the entire fresh produce supply chain. Overall, by focusing on the interoperability and offering user-friendly and open access IoT services, AgroTRACE aims to bridge the gap in fresh produce traceability and bring added value to the products.

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