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Convergence of Distributed Ledger Technologies with Digital Twins, IoT, and AI for Fresh Food Logistics: Challenges and Opportunities

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ABSTRACT

The growing demand for fresher and better quality food products has led various researchers to propose solutions in this field. Besides the increase in food production, the efficiency of food logistics must be improved to reduce waste. An efficient food supply chain also reduces the final cost of products, increases producers' incomes, mitigates the environmental impacts, and allows transportation of fresher, healthier foods. Collection and analysis of information on product tracking and stakeholder demands can improve supply chain efficiency, providing important insights to managers. Technological solutions, such as the Internet of Things (IoT), Artificial Intelligence (AI), Digital Twin (DT), and Distributed Ledger Technology (DLT), have been proposed for monitoring and tracking products and analyzing data collected while supporting decision-making. However, there are still few studies about the integration of these technologies, especially DTs, intelligent models, and DLTs. Thus, this work presents a review of the application of these technologies for food logistics, identifying the main requirements and summarizing how they can be applied in each logistics stage. Related surveys are discussed to find gaps in the literature and six research questions are defined and answered, aiming to argue about how the chosen technologies can be applied and combined to attempt the identified requirements. Lastly, this work discusses research opportunities in the fresh food supply chain, presenting some open challenges for adoption while integrating these technologies.

1. Introduction

Logistics of perishable products is a complex operation. It has many requirements, such as product traceability and monitoring, due to food's high perishability and contamination risks. Moreover, it is an often inefficient operation. Due to the large variety of fresh foods, grown and cropped in smaller quantities, it is increasingly difficult to have a full truck of products ready for shipment at a given time. The perishability of products leads managers to make quick decisions to avoid quality loss and end up sacrificing efficiency in the process. Estimates show that the efficiency of trucks and trailers is in the 10 to 20 percent range, and food spoilage and waste estimates are in the 12 percent range [1], causing economic and environmental impacts since capacity is underutilized, often a problem referred to as "shipping air". In addition, bad practices in product handling cause food waste and loss during the logistic process. It is estimated that one-third of all food production is discarded [2]. In developing countries, the lack of an efficient infrastructure for storage and transport is the main factor. In India, it is reported that about 35% to 40% of the fresh products are lost after harvesting due to several factors including spoilage or pest [3].

Among the many causes of the pointed problems is the lack of transparent and accessible information through the supply chain [4]. As the products pass from one actor to another through the supply chain, less information about their origins is available. Despite the information on food labels, little is known about the real-time condition of the products during logistics and spoilage often occurs. Poor information about food products, in addition to reducing consumer confidence, brings inefficiency and waste to actors in the supply chain.

Diverse outsourced logistics service providers have been emerging in this context, providing their expertise in management and technology to improve operations efficiency, reduce costs and deliver better quality products. However, they are highly dependent on data about logistics processes. In this scenario, collaboration among logistic providers is fundamental to better utilization of logistics resources, such as trucks and warehouses [5]. Due to a lack of trust among actors, information is generally isolated in the private clouds. Without precise information, service providers cannot share resources among them and cannot route and schedule carriers optimally, causing delays in transportation. Moreover, consumer demands are nebulous for most actors, making the decisions about production, storage, and transportation increasingly imprecise.

Digital Twins (DTs) have been advancing supply chain visibility in several areas of industry [6]. Supported by the Internet of Things (IoT) [7, 8] and Artificial Intelligence (AI) [9], DTs can create accurate models of physical assets and products, following their status in real-time and improving decision-making by simulation techniques [10]. On other hand, Distributed Ledger Technologies (DLTs), like Blockchain, for example, have been employed to trace food and agricultural products through the supply chain trustfully and without the need for a central authority [11]. Together with IoT solutions, the complete history of food products can be automatically registered [12, 13]. By employing Smart Contracts (SCs) with programmable clauses, data can be automatically verified, triggering different actions and business among actors is supported [14].

The integration of these technologies has been changing how data is collected, shared, and analyzed through the food and agricultural products supply chain and has the potential to make a large improvement in fresh food logistics requirements. Different literature research has been

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exploring these technologies to solve or mitigate the pointed problems. However, few studies consider all requirements of an efficient operation or discuss the enabling technologies and integration among them to attempt these requirements.

The objectives of this paper are: (i) to present the current state-of-the-art in studies about the food supply chain; (ii) to identify the main requirements of food logistics; and (iii) to review the latest solutions to attempt these requirements while integrating IoT, AI and DT with DLT and Smart Contracts, pointing open challenges and research opportunities. This revision focuses on fresh food logistics and shows different scenarios for the integration of the mentioned technologies, considering conceptual and technical aspects. This work guides future research in the food and agriculture supply chain, presenting the following contributions:

- A specification of functional and non-functional requirements for fresh food logistics support systems, which will be detailed in Subsection 2.1.
- A comprehensive review of literature solutions applying DLT and DT technologies, with IoT and AI support, to meet each of the requirements specified for the fresh food logistics process.
- A discussion of how DTs and DLTs can be integrated to meet all requirements simultaneously, presenting challenges and research opportunities.

The remainder of the paper is organized as follows. Section 2 presents important concepts about fresh food logistics and the technologies considered in this research. Section 3 summarizes the related revisions present in the literature and points out gaps regarding the Fresh Food Logistics (FFL) requirements. In Section 4, the methodology employed to collect literature articles is presented and the works found are analyzed. In Section 5, research opportunities in the FFSC are discussed and some open challenges for adoption while integrating these technologies are presented. Lastly, Section 6 concludes this paper and suggests future works.

2. Background

In this section, important concepts related to this work are presented. First, supply chain aspects are described, detailing the specific characteristics of the fresh food supply chain. Then, some of the important technologies for this work are presented, as well as their potential applications in fresh food logistics.

2.1. Fresh Food Supply Chain

The term supply chain is used to define a network of interdependent organizations that are jointly involved in the necessary activities to meet end-consumer demands, delivering products or services [15]. A company becomes more competitive when it is inserted in an efficient SC, being able to guarantee better prices and better quality in the products or services delivered. With globalization, the distance between end-consumers and producers has increased, as much as the number of intermediaries in the chain. Delivering high-quality products with low operational costs in this scenario has become a complex process and hence the product's final price is impacted.

To handle food products in a supply chain, specific care must be taken, due to their perishability and the risk of contamination. When the perishability of a product is very critical, as in the case of fresh food, the complexity of the logistics processes is even greater. This chain can be called cold chain [16], perishable supply chain [17], or Fresh Food Supply Chain (FFSC) [18], as it will be called in this paper.

The FFSC has a lot of particularities, such as different actors, routing, scheduling, and special care with the batches [19]. Therefore, actors in the FFSC and the commercial relations among them have some specific characteristics. A holistic view of the FFSC actors and their possible connections is shown in Figure 1. The internal circle represents the flow of materials and food products. Actors in the internal circle are involved with handling food directly. The arrows represent the logistic process among actors, executed normally by Distributors (that means this actor can participate in all transactions indicated by arrows). The external circle represents the information flow. Actors in the external circle only deal with information. Each actor and their relations are defined below.

- Raw material providers: Food producers that supply the processing industries, associations, retailers, or directly the end customers (Flow 1). They are large or small farmers, which may include community gardens caretakers.
- Farmer's associations: Organizations composed and managed by rural producers with the objective of increasing the volume and quality of the food produced and improving the income and efficiency of the members' operations. They can have their own food process operations or sell products to industries or retailers (Flow 2).
- Manufacturing enterprises: Industries responsible to process food. Canning, frozen meat, and brewing industries are examples of manufacturing actors. They supply retailers with processed products (Flow 3).
- Retailers: Actors who store, prepare, and resell food to the final consumer (Flow 4). Supermarkets and restaurants are examples of this type of actor.
- Distributors: Intermediaries that store and/or transport natural or processed foods before they reach vendors or end consumers. They are Third-Party Logistics (3PL) providers or divisions of large industries, associations, or retailer companies. They possess and maintain logistical resources, such as trucks and warehouses, and they are present in the whole supply chain.
- Fourth-party Logistics (4PL) providers: They are outsourced companies that provide logistic management

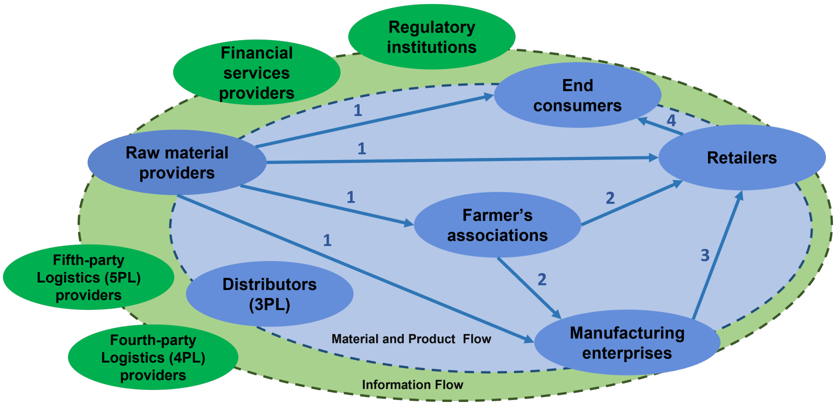

Figure 1: Fresh Food Supply Chain model.

services, including resource allocation, routing of deliveries, and purchase of inputs for their clients' manufacturing processes [20]. They can assume the whole logistic operation of other companies, allowing them to focus on their production process.

- Fifth Party Logistics (5PL) providers: Technology-focused service providers to optimize logistic operations and reduce costs [21], which include hardware for monitoring and software for simulation and optimization, for example.
- Financial services providers: Banks, insurers, or companies that lead with financial transactions between actors. Currently, DLTs can enable these transactions without the need for intermediaries and several companies have taken advantage of this technology [22].
- Regulatory institutions: Governmental departments, certification companies, or auditory agents responsible to ensure products' quality and consumer security.
- End consumers: Actors at the end of the chain who consume food products.

The FFL process has complex requirements and it is subject to different hazards [23]. Table 1 summarizes the requirements considered in this paper, which are discussed following. Each type of product in the FFSC has special transport and storage requirements. For example, some of them may have a high humidity or temperature variations sensitivity (hence the definition "cold chain" can also be used) [24], besides their fragility for the mechanical damages, which can be caused during the transportation. These conditions must be monitored throughout the movement to track food downstream and to help distributors deliver better quality and safer products (R3). Without real-time monitoring, actors may belatedly realize that a product is inappropriate for consumption, causing waste.

Furthermore, the safety of consumption must be guaranteed. In addition to the tracking requirement, which is real-time monitoring of position and conditions, regulators and consumers need to access information on product traceability, which is the history of products from farms to retailers [25] (R2). Legislations on food tracing, such as Brazilian law [26] and European regulation [27], are already in effect today. To correctly trace products' history, a unique identification must be associated with a product or a batch (R1). In addition, easily corruptible identifiers are a problem that can affect the food chain, losing information about products, causing data inconsistency, allowing data tampering, or other malicious actions. Therefore, an appropriate design of globally unique identifiers is required. This information also helps in the recall of contaminated food, identifying the exact batch or batches that need to be removed from the gondolas, for example, mitigating food loss and waste [28]. However, the register needs to be fraud-proof to meet these requirements (R2).

As a second aspect, the food logistics decision-making process must consider several aspects, such as the momentary and future quality of the products, better usage of available logistic resources, and the expected demand of actors [29]. In this way, it is important to monitor the logistics resources status, considering their availability, capacity, fuel consumption, conditioning aspects, and so on (R4). Supported by data about products' and resources' monitoring and tracing, better decisions can be made. With the lack of up-to-date and accurate information on logistics resources, managers cannot make better decisions to optimize the use of these assets and reduce operating costs. 4PL and 5PL providers are companies acting to attempt these requirements and improve logistics processes efficiency (R5). It is currently unfeasible to make optimal and fast decisions without the help of information technology. However, many of these methods are data-driven and the lack of current and transparent information can harm the results.

Lastly, coordination and collaboration among actors are fundamental. Decision-making is harmed due to food products' perishability, constant variations in demand, isolation of information, and mistrust among the actors [30]. During the COVID-19 pandemic, food suppliers had to quickly adjust to changing consumption habits [31]. Moreover, information isolation among actors hides the potential for partnerships to optimize resource utilization and reduce

Table 1
Food logistics requirements considered in this paper.

Requirement	Description
R1	Unique and uniform identification of food products and logistics resources.
R2	Transparent and trustful sharing of data about food products tracking and tracing.
R3	Real-time monitoring of food products quality using environmental conditions during transport and storage.
R4	Monitoring of logistics resources status.
R5	Decision support for resource allocation, routing, products quality evaluation and demand prediction.
R6	Trustful ecosystem for collaboration and coordination among logistics service providers.

costs. For example, two half-full trucks of different actors can leave from the same region to deliver food products, to nearby destinations, without the knowledge of both actors. With a trusted ecosystem to foster information and resource sharing, logistic providers can improve their responsiveness and execute more efficient processes (R6).

2.2. Technologies for Fresh Food Logistics

Current Information and Communication Technologies (ICTs) can automatically collect and process data through the FFSC and have been used to attempt the FFL requirements, reducing fresh food waste and loss and maximizing the quality of delivered food. In this paper, we consider DLT and DT-based solutions, integrated with IoT and AI technologies. Table 2 shows how these technologies can be integrated to meet each of the requirements, as further explained following. Concepts about some of these technologies are discussed in detail in the next Subsections, as well as how they can be applied in FFSC solutions.

IoT solutions, such as devices with Radio Frequency Identification (RFID) readers, can be applied to automatically identify batches of products and logistics resources (R1). In addition, different sensors, such as temperature, humidity, luminosity, pressure, impact, and so on, can be integrated with these devices and collect data about the environmental conditions that food products are exposed to during logistics (R3). Data about the logistics resources status, such as fuel level and consumption, location, odometers, and so on, can also be collected by IoT devices (R4). These data can be transmitted via different communication technologies, such as SigFox, LoRaWAN, 3GPP standards, Wi-Fi, Bluetooth, 6LoWPAN, and others, depending on distance, mobility, throughput, and latency requirements, besides IoT devices' limitations.

Data collected during the logistics process can be used by AI and different data-driven methods to support management decisions (R5). Food product quality can be improved by machine learning techniques and specialized systems that can control conditioning systems, estimate quality based on monitoring data, and predict shelf life. Logistics efficiency can be improved by evolutive algorithms and different optimization techniques applied to maximize resource utilization, based on data about, product quality, vehicles and warehouses, traffic, consumer demands, and food production.

Table 2
Technologies for fresh food logistics requirements.

	Technologies				
Requirement	**IoT**	**AI**	**DT**	**DLT**	**SC**
R1	×			×	
R2				×	×
R3	×		×		
R4	×		×		
R5		×	×	×	
R6			×	×	×

Furthermore, data can be used to maintain DTs of food products and improve the monitoring of food conditions (R3). DTs of logistics resources can improve the visualization and remote control of logistics operations (R4). These DTs can be applied in supply chain simulation to generate important insights and help in the planning and execution, optimizing decisions during the logistics process (R5). In addition, DTs can facilitate information sharing and service provision among actors in all logistics steps (R6).

Finally, DLT can store data about products and resources immutably and decentrally, providing identification and authentication for actors (R1). Consensus mechanisms and SCs intermediate data insertion and bring trust among participants. The decentralized nature of DLT improves data transparency and availability (R2). This transparent data can be used by all actors to support decision-making (R5). SCs make available the commercialization of products, resources, logistics, and optimization services (R6).

2.2.1. *Internet of Things*

IoT term is first cited in 2009 [32] to describe an architecture that enables physical objects to share natural world information with users or other objects; to be controlled remotely and execute their functions automatically. The components that support this architecture are usually simple low-cost micro-controllers with embedded software, equipped with batteries, sensors, actuators, and communication technologies, generally wireless.

RFID is an enabling technology for IoT. It usually adopts passive tags, composed of a chip, with a code number, and antennas to transmit this information to a radio base. These tags can send info at a relative distance and the base can read thousands of tags simultaneously. Some tags can act as passive temperature, pressure, moisture, etc. sensing. Another alternative proposed for identification is Near Field Communication (NFC). RFID generally needs specific devices with antennas to read information from tags. It is common to occur interference in RFID reads in very humid environments. NFC is a newer and improved version of the same RFID technology more resistant to interference. Recent smartphones have NFC readers that can be controlled by applications. These technologies can help to identify the product batches and the logistic resources employed to transport and store these products automatically, avoiding input errors [33] (R1).

Also called Single Board Computers (SBCs) are the central part of an IoT device. Arduino, Raspberry, and ESP32 are examples of this kind of device. They can monitor temperature, luminosity, or other physical magnitudes using sensors and modify the physical world using actuators, e.g. a switch to turn on a lamp. These devices can be installed on product batches or logistics resources and can support real-time monitoring of food products and resources status during logistics processes (R3, R4), in addition to actuating on triggering the air conditioning and ventilation systems, for example.

The communication protocols adopted by an IoT device have particular requirements [34]. The same is valid for the application layer protocols [35]. IoT devices have resources limitation and need to operate using low power, in the presence of lossy and noisy communication links, and with high mobility requirements. In FFL, different communication technologies can be applied for different levels of monitoring, for example, the devices that monitor a warehouse are different from those embedded in a product batch, due to power and mobility needs. Current solutions generally employ cloud servers to store and process data and make information available to applications and users. In very dense and complex IoT environments, an intermediary platform, also called middleware [36], can help hide implementation complexity from the user.

2.2.2. Decision Support and Artificial Intelligence

Decision support systems are very important in supply chain management and logistics, especially for fresh food and perishable products. These systems evolve all techniques used to process data and generate important information for managers, on a strategic, tactical, and operational level. The main objectives are to solve optimization problems, such as: resource allocation, routing planning, and supply chain design, as well as demand forecasting, inventory management, and so on. Conventionally, numerical methods, such as Simplex, and other programming methods, such as: linear, non-linear, multi-objective, stochastic, fuzzy, heuristics, metaheuristics, and hybrid programming [37] are applied in this context, depending on the problem characteristics. Some kinds of complex problems cannot be easily solved in polynomial time, called NP-Hard problems, and would take a long time to be exhaustively processed. Heuristics and meta-heuristics approaches aim to solve these problems by approximating better results. Lately, AI techniques, such as: Artificial Neural Networks, Fuzzy Logic, and Genetic Algorithms have also been employed to solve different supply chain management problems [38].

The concept of AI has been discussed since 1940 but was officially defined around 1960 [39]. It comprehends systems that try to simulate natural and human intelligence on some level. However, current solutions still have been employed to solve specific problems. Evolutionary Algorithms (EA) are an approach of AI that simulates biological evolution mechanisms to explore solutions for complex problems [40]. They are applied to single or multi-objective optimization problems, providing adequate solutions even with limited computation capability and insufficient or imperfect information. In logistics and operation management, genetic algorithms can be applied in different decision areas, such as: facility layout design, supply network design, job design and work, forecasting, capacity planning, inventory control, scheduling, maintenance, and risk management [41]. An application example is to minimize the cost of transportation by choosing the best available providers based on data about their logistics resources (R5).

Although there is great fitness with optimization, AI can also be applied in control, classification, clustering, and regression. One of the first approaches to AI was the Expert Systems[42], which incorporates specialists' knowledge about a specific domain to create mechanisms to solve narrow problems. The rule-based inference process in fuzzy logic adopts the concept of expert systems [43]. Based on real-time data, these rules can help to trigger conditioning systems to optimize food product quality, for example (R5).

Machine Learning (ML) is the most popular AI technique and aims to create learning behavior in machines by a software model that improves its performance by training under previous data [44]. It is normally adopted for prediction, classification, and clustering, being applied for speech recognition, computer vision, and robot control. With this technique, the quality of a product at the end of a process can be predicted based on environmental conditions of transport or warehousing, or the best route for delivery can be defined on the road based on traffic data (R5).

2.2.3. Digital Twins

This definition was first made by Michael Grieves in the early 2000s in a presentation and later published as a white paper [45] and as a book chapter [46]. DTs are defined as representatives of physical world entities in a virtual environment based on data. In Cyber-Physical Systems (CPSs) [47] they are employed to monitor and control devices, machines, vehicles, and even people. With the emergence of IoT, several DT-based solutions have been improved in different applications [48]. These representations can support simulation, optimization, and prediction, improving decision-making in several areas, such as manufacturing, healthcare, and smart cities, enabled by different technologies, such as modeling and simulation software, IoT, and AI [49].

The creation of DTs is a multidisciplinary activity. With the advance in IoT, sensors, and telecommunication technology the models are improved with real-time data. AI algorithms analyze arriving data, generating important information. Besides those technologies, 3D modeling, Virtual and Augmented Reality helps with visualization and control [50]. Applying DT in FFL, food products models can be created to improve the quality visibility during the logistics processes (R3). Moreover, logistics resource models can be created, such as warehouse or container 3D models, to improve their status visibility (R4). These models can be employed in simulation and optimization software to improve logistics process efficiency (R5). Using the digital models of logistics resources, a 3PL provider can offer them in e-commerce and clients can choose the better option available (R6).

When the representation is described only as digital version of a physical object, it is called a digital model. Once created, the digital model does not change its status automatically, that is, there is no form of automatic data exchange between the physical system and the digital model. On other hand, if the digital representation changes its state when there is a change in the physical object state, but the opposite does not happen, the representative is called a digital shadow. DTs allow two-way data exchange between digital and physical objects.

There are different DT models, which are physics-based, data-driven, statistical, and theoretical models. The approach mostly employed is physics-based, which consists of formulating and solving mathematical equations about understood phenomenons, applying relevant physical, biochemical, microbiological, and physiological processes obtained from multiphysics modeling and simulation. With the advance in AI techniques and Big Data, data-driven models can be developed, calibrated, verified, and validated, using lots of preexisting data about the physical entity. Statistical models are mathematical formulations built and calibrated empirically with experimental data, like kinetic rate law for example [51]. Finally, theoretical models are based on analytical calculation considering only very simple and specific scenarios, disregarding uncertain factors.

2.2.4. Distributed Ledger Technology

DLT [52] is an alternative for many centralization problems brought by cloud computing, such as single point of failure, hacker attacks, privacy lacks, and data tampering. A cloud server must be robust and secure, increasing building, renting, and operating costs. A distributed ledger is a way to decentralize data storing and communication. A DLT provides distributed systems for securely and privately storing data. It eliminates the need for a third-party authority through the implementation of Peer-to-Peer (P2P) communication protocols, cryptographic algorithms, and consensus mechanisms. Data on a DLT is:

- Transparent: DLT nodes can keep the entire ledger and any node can access the history of transactions.
- Immutable: Data in a transaction is encrypted in verifiable hash code. In this way, any change in transaction data can be identified.
- Verified: The encryption process applies the private key to "sign" a transaction and with the public key it is possible to verify the author.
- Consented: To insert transactions on a DLT, nodes need to reach an agreement through some established process.

When a new node wants to enter the network, it must be approved. Depending on the application requirements, a DLT can be public, private, or consorted (also known as federated or permissioned). On a public DLT, anyone can join the network and become a part of it. A private DLT grants permission and restricts access to the network, being mostly applied within an organization, and available only to particular members. Consortium DLT is a combination of both types. In this type, there is more than one organization involved that provides access to nodes.

One of the DLT models is the Blockchain. It was first proposed in a white paper [53] as the system behind Bitcoin. Today there are many other implementations, like Ethereum and Hyperledger. Blockchain checks and records transactions in sets called blocks. In addition to transaction data, the hash value of the predecessor block is also inserted into the content of a block. Thus, the block data is encrypted and the hash value of the current block is inserted into the successor block. The initial block is called the genesis block and does not have a predecessor. All committed transaction blocks are linked and chained from the beginning of the chain to the most current block, hence the name Blockchain.

Tangle is a new DLT employed by IOTA, where records are inserted into a Directed Acyclic Graph (DAG) and distributed over the network. All nodes in the network are responsible for approving transactions, which removes the role of miners in the network. There are no mining fees at Tangle, making micro and even nano payments easier [54]. One of the reasons for the existence of this digital currency is the possibility of transactions between IoT devices [55].

To validate and insert a transaction in a DLT, some consensus must be made among network nodes. A transaction is inserted only if a certain number of nodes agree. There are different mechanisms in the current implementations of DLT. Some examples of consensus mechanisms are Proof of Work (PoW), Proof of Stake (PoS), Practical Byzantine Fault Tolerance (PBFT), and Proof of Elapsed Time (PoET) [56].

DLTs have been employed in different kinds of applications, such as finance, healthcare, industry, and agriculture. In FFL, this technology has the potential to provide trustful traceability of products during the whole operation (R1, R2). Especially when it is integrated with IoT, the history information quality about products' life cycle can be improved. The integration of DLTs with DTs has been studied and the benefits found include trust data coordination, fine-access control, identity and legitimacy of models, and decentralized infrastructure, in addition to data immutability, transparency, and accountability [57, 58]. DLT applications for AI also have been surveyed and were pointed out many benefits, such as the decentralized infrastructure and servitization, and challenges, such as security, trusted oracles, scalability, consensus protocols, and standardization [59]. For example, SingularityNET is an open-source protocol, based on DLT smart contracts, for a decentralized market of coordinated AI services, aiming for the creation of a global common infrastructure [60] (R5, R6).

2.2.5. Smart Contracts

Smart Contracts (SCs) are sets of programmed clauses registered in a distributed network [61]. Although smart contracts are implemented in the context of the DLT, the concept behind them was introduced before the Blockchain proposal [62]. In practical terms, the SC "code" is registered on a DLT as a transaction. So, each node that has access to the ledger can run this code. SCs work in such a way that, when a predetermined event occurs, another predetermined action will automatically take place. Furthermore, they are executed without the need for human action, as the code itself checks each step, seeking to fulfill what was assigned. Since they are run from the DLT as they were published, they cannot be changed at runtime (deterministic running), thus providing a further guarantee of security. These features support the sale of services and products on a DLT [63]. FFL actors can sell their digital services, such as optimization and routing, or even their physical services, such as transport and storage (R6).

2.2.6. Oracles

Oracles are intermediary entities that bring off-chain (out of the DLT) data to be used on-chain. Generally, they provide off-chain data to a SC or to help with interoperability between different distributed ledgers. The objective of an oracle is to implement mechanisms to enhance trust in off-chain data [64], such as reputation, voting, or incentive mechanisms. There are three ways to obtain this data: hardware oracles, which receive data from scanners or sensors and send data to verify compliance with contractual clauses; software oracles, which deal with data from web APIs; and human oracles, which treat data inserted by actions of human operators. The oracles can be implemented on-chain, as SCs, or off-chain, as DLT nodes [65]. Therefore, oracles can help with the insertion of FFL data on a DLT, especially when data is automatically collected by IoT devices (R2).

3. Previous Work

Several works have been made to survey or review the application of previously mentioned technologies for the food supply chain. In this section, related revisions in the literature are discussed. Table 3 relates each of the previous works with the food logistics requirements and the technologies discussed.

Solutions in the "agriculture 4.0" domain, an analogy to "industry 4.0" that covers emergent technologies like IoT, Big Data, Artificial Intelligence, Robotics, and Blockchain applied in the industry scenario, have been reviewed. These technologies have made important information more accessible to farmers and managers to support a better food supply chain decision-making process [66]. The current state of production patterns and processes in agriculture and the food supply chain have been presented, as well as the key applications and challenges of these technologies [67]. However, these revisions have focused on food production aspects, reviewing a few solutions for logistics management. "Food logistics 4.0" also has been discussed in the literature, as well as how these technologies can improve efficiency and build customers' trust in the food products [68], but did not cover the integration of different technologies to attempt the food logistics requirements.

Literature reviews focusing on IoT technology applied to the perishable food supply chain have been discussed in the following works. Villalobos et al. [70] covered how IoT allied to Big Data predictions has supported strategic, tactical, and operational decisions taken from actors in each step of the supply chain, from farms to retailers. The causes of food loss and waste, such as refrigeration during transport and storage problems, food safety concerns, inconsistent and confusing date labels, and delays during border inspections, have been related to sensing/communications infrastructure, such as Time and Temperature Indicator (TTI) tags, ripe and contamination sensors, RFID, Ultrasonic and Magnetic Induction (MI) [71]. Using relevant information collected by temperature, humidity, and CO2 sensors, for example, IoT has been applied in advanced agriculture and detection of food quality and shelf life, an important research area [72]. Moreover, IoT technology for smart agriculture has been classified into physical, network, service, and application layers, and the integration of Blockchain and IoT also have been related to traceability and tracking in food supply chains [69]. Although these reviews consider almost all food logistics requirements, logistics resources management has not been considered.

DT technology applied to agriculture has also been reviewed in the literature. Solutions have been dealing with animal and plant DTs for health monitoring, agricultural products' DTs for quality estimation, and agricultural assets' DTs, such as machinery, fields, greenhouses, silos, and other buildings, to support decision making [73]. Although some solutions have improved supply chain efficiency, the majority of them have been focused on production aspects. Key advantages of DTs for the supply chain of fresh horticultural produce have been identified in [74]. DTs can help to estimate more precisely the misty evolution of food quality, tracing the history during the products' life cycle, and provide actionable data for actors when defining better strategies, avoiding food waste and loss. Although these reviews cover solutions for requirements R3 e R5 of food logistics, they do not consider the application of DTs to

Table 3
Summary of surveys and reviews related to the current research.

	Requirements						Technologies				
Previous Work	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**IoT**	**AI**	**DT**	**DLT**	**SC**
[66, 67, 68, 69]		×	×		×		×	×		×	×
[70, 71, 72]	×	×	×		×		×	×		×	
[73, 74]			×		×		×	×	×		
[75, 76, 77, 78]	×	×					×			×	×
[79, 80, 81]	×	×	×				×			×	

the management of vehicles, warehouses, and other logistics resources.

The benefits of DLT applications for the FFSC have been presented in several literature reviews. Blockchain has been employed to resolve several issues, such as data integrity, tampering, single points of failure, transparency, traceability, auditability, information asymmetry, and lack of standardization in data format [75]. Notwithstanding, this technology has been improving data management of smart farming and other agricultural-related processes, and the efficiency of the trade in the supply chain [76]. Among the technical requirements, there are IoT data acquisition and transmission, data security, information transparency and data sharing, and some performance requirements, like transaction speed, system adaptability, reliability, stability, and scalability [77]. Feng et al. also covered deployment issues [77]. Other DLT-related challenges that have been discussed include privacy, cost, interoperability with different DLTs and other technologies, energy consumption, and storage [78].

The integration between IoT and DLT is a relevant research topic and has been applied to solve some supply chain management challenges, such as the lack of visibility from the upstream side to the downstream side, the missing flexibility to respond to sudden changes in demand and to control the consequent increase in the cost of the operation, the lack of trust on security among stakeholders, the ineffective supply chain risk management and the lack of advanced technologies [79]. The main application covered is an inventory, quality management, and food-borne illnesses tracing. Organizations that apply Blockchain in their operations have been cited, like Dole, Unilever, and Walmart, which are partnering with IBM in its FoodTrust initiative [80]. Notwithstanding, the adoption of "permissioned" Blockchains is considered essential, due to the different data privacy policies and parties with a variety of roles (for example, regulators, inspectors, shippers, and sellers). Applications in the early stages of the food supply chain, such as crop overseeing, land registration, and financial transaction among farmers, or among farmers and agricultural organizations have been considered in [81]. Some applications in other steps of the supply chain were presented too, such as data recording, monitoring, verifying, and sharing to promote trust among actors and food safety.

As previous works show, DLTs have become a key technology for the logistics of food and agricultural products. Blockchain, for example, has been applied to securely and transparently store data, providing an immutable history of each product. Supporting that, wireless sensor networks composed of IoT devices can collect many kinds of data about environmental conditions, localization, and so on, during product transportation and warehousing. AI methods have been employed to extract information from huge amounts of data, creating automation and supporting decision-making in different operations. DTs supported by IoT and AI models have helped to better visualize the status of products and logistics resources. Although the DLT integration with IoT is widely treated, few literature reviews consider the application of intelligent models using DT and AI in DLT-based solutions. Moreover, few works have addressed the potential of DLTs and smart contracts to support the digital servitization of logistics. To the best of our knowledge, this paper provides the first convergent review on DLT-based DTs for FFL.

4. Literature Review and Discussion

Aiming to better understand how DTs, IoT, and AI can be integrated with DLTs and SCs to attempt food logistics requirements, a comprehensive revision of literature solutions has been made and will be described in this section. Six research questions have been defined to guide the selection of relevant literature articles and they are presented in Table 4. The chosen terms to perform the search are: (food OR perishable OR agriculture OR agricultural) AND (warehouse OR inventory OR distribution OR delivery OR transportation OR logistics OR logistic OR "supply chain") AND ("distributed ledger" OR blockchain OR "smart contract" OR "digital twin") AND ("internet of things" OR IoT OR "artificial intelligence" OR "machine learning" OR "evolutionary algorithm").

To pre-filter the results, the search for terms considered only the title, abstract, and keywords of the papers. First, the keywords "food", "perishable", "agriculture" or "agricultural" were applied to select all papers related to this area. Second, the keywords "warehouse", "inventory", "distribution", "delivery", "transportation", "logistics", "logistic" or "supply chain" were applied, aiming to select only papers about food logistics operations. Third, we applied the keywords "distributed ledger", blockchain, "smart contract" or "digital twins" to select the papers that consider the application of these technologies. Lastly, we apply the keywords "internet of things", "IoT", "artificial intelligence", "machine learning" or "evolutionary algorithm" to filter only papers that cover these technologies combined with DLT or

Table 4
Research questions.

Question	Description
Q1	How can technologies in the IoT and DLT scenario help to identify food products and logistics resources through the supply chain?
Q2	How can DLTs and SCs validate, store and share tracking and tracing data collected among the actors?
Q3	How can DT and IoT devices monitor the environmental conditions and provide information to managers during the transportation and storage of food products?
Q4	How can DT and IoT devices help to create a digital representation of logistics resources to monitor their status?
Q5	How can DT based on AI models analyze data about food products and logistical resources, registered or not on a DLT, to support the decision-making process?
Q6	How can DT, DLT, and SCs assist in establishing logistical services and define contract clauses on product transport conditions?

Table 5
Quality assessment criteria.

Criteria	Description
1	Filter looking for a period of 5 years: 2016 up to 2021.
2	Remove books, technical reports, dissertations, and thesis.
3	Remove documents less than 4 pages long and that are not in English.
4	Remove all publications that do not propose new solutions to fresh food logistics.
5	Remove all publications that do not address at least one food logistic requirement and that do not employ at least one of the technologies covered in this paper.

DT. The papers for the literature review were selected from different publishers, including IEEE Xplore (113 results), Elsevier Journals (36 results), ACM (4 results), and MDPI repositories (22 results). Finally, after reading the abstracts, the search results were selected according to the exclusion criteria shown in Table 5.

Results of our review are discussed next, aiming to answer each of the proposed research questions by discussing literature accordingly to the following issues: (i) entities identification; (ii) traceability; (iii) food products monitoring; (iv) logistics resources monitoring; (v) decision support; and (vi) ecosystem for logistics providers. In other words, answers to the literature research questions will emerge in the context of such CPS issues. Table 6 shows the selected papers and how they support the answers to the research questions.

4.1. Identification

Each actor on the FFSC needs an identification (ID) to be able to insert, transport, warehouse, process, or sell product batches on the supply chain. The actors' resources, such as a container, carrier, or warehouse, also need an ID. There are many forms to identify an actor or a logistic resource but generally requires a central authority to maintain these IDs. In a DLT this ID can be generated and stored in a decentralized way, using public keys that are associated with registered transactions (Q1). Depending on whether the DLT is public, consortium, or private, a new member may need to be approved by a minimal number of members to reach an agreement while entering the network. Once entered into the network, they can insert new transactions. In [95], actors compose the P2P overlay network, responsible to initialize the communication and accept new nodes, using SCs, and identifying the members by public keys (Q1).

Before an item is entered into the logistics process, a unique ID also must be assigned to it. The product ID can be defined right after the harvest. Like actors and logistical resources, the products can be identified in different ways, e.g. using the GS1 standard, however, some approaches can bring centralization problems. On a DLT, each product batch can also be identified with a public ID, generated by algorithms, stored in all nodes, and known by all actors, and the monitoring data about it is registered on the DLT with a transaction that contains the product ID (Q1). All information about this item is associated with its identification, such as production and manufacturing processes and storage and transport conditions [121], for example, as well as the identification of the resource and the actor involved (Q2).

On the other hand, IDs are large strings of numbers and letters and handling this data manually in a real operation can be difficult. For example, the public keys are large hexadecimal codes generate by an algorithm. However, a physical component can facilitate the reading process of these IDs, like optical scanners or IoT devices that can automatically read the IDs recorded in tags inserted on product batches, avoiding entry errors and reducing the risk of tampering (Q1).

For each type of product, a granularity level must be defined. For example, in the fruits logistics process, a unique identification for each fruit may not be feasible. There are also products that must necessarily be put together in lots, as in the case of grains and milk. In this case, a minimum feasible batch is assembled, defining the amount and type of product units in a package, and identified through a production batch code, containing information such as the production day and the list of raw materials used (Q1) [89]. On the other hand, high-value products such as a special wine bottle, for example, may require an identification per item [122].

Big item amounts move simultaneously through the supply chain and can share storage and transportation resources. Thus, a standard must be adopted to generate an unrepeatable identification for each material or product (Q1). Many solutions for the FFSC adopt some standards managed

Table 6
Selected papers and how they answer aroused research questions.

Research Question	Answers	Papers Related
Q1	GS1 standards Bar and QR code can identify small or low-value food product batches.	[82, 83, 84]
	GS1 standard EPC can identify larger or high-value food product batches.	[85, 86, 87]
	Optical and RFID/NFC readers can automate the identification process.	[88, 89, 90]
	IoT devices can represent large product batches or logistic resources.	[91]
Q2	Public DLTs can provide immutable and transparent food products data storage.	[92, 93]
	Consensus mechanisms and oracles can improve data credibility.	[94, 95]
	Private/Permissioned DLTs can improve actors' privacy.	[96, 97, 98]
	SCs can intermediate and facilitate data registration processes on a DLT.	[99, 100, 101]
	Combination of cloud and DLT can improve data storage efficiency.	[102]
Q3	Diverse IoT sensors can be employed to monitor food product quality throughout the logistics processes.	[103, 104]
	DTs of food products can be applied to improve the accuracy of product quality monitoring.	[105, 106]
Q4	IoT sensors can monitor the conditioning and other logistics resource status.	[107, 108]
	DTs of logistics resources can be applied to improve the resources, processes, and supply chain visualization, management, and control.	[109, 110]
Q5	Machine Learning and Fuzzy logic can be applied to food product quality evaluation.	[111, 112]
	DTs can be employed in simulations to support decision-making.	[113]
	DLT data can be processed by machine learning and applied to demand forecasting, profit optimization, and routing optimization.	[114, 115, 116]
Q6	DLT data can feed visualizations about products, market supply and, demands for all actors.	[117]
	SCs can be applied to manage trade and service provision transactions among actors.	[118, 119, 120]

by GS1, due to its dissemination in the market, and one least of the fast reading formats, such as the bar code, the Quick Response (QR) code, and the Electronic Product Code (EPC) for RFID technology [123].

Unique identification is also fundamental to tracking and tracing a product. All information collected in the production and logistics stages must be available to any actor in the FFSC [124]. In literature, some main technologies and standards are adopted together to efficiently identify the items in the FFSC. These are detailed next.

4.1.1. Barcode and Quick Response code

These codes are image standards employed for fast recognition of numbers and, in the case of QR codes, alphanumeric information, such as URLs, nutritional information, and expiration date for example. Almost every product on the market has one of these codes on its packaging, due to the relatively low cost associated with its generation and use. The equipment adopted to read these images is relatively simple optical sensors. Therefore, vision contact and short distances are required, making the identification process more complex. However, these codes are highly indicated for consultation by the consumers. Consumers can access product information, e.g. registered decentrally on Blockchain (Q1), using a smartphone application that accesses the camera to scan the Bar or QR code found on the food item they are buying [82, 83].

In the FFSC solutions, these methods are indicated when the granularity needs to be low, that is, the required number of identifiers is large and the price per identifier should be as small as possible. Generally, it is applied to identify food products or manufacturing inputs. In [84] QR code has been employed to identify an ice cream machine and the ingredients, thus allowing to identify the producer and flavor of the ingredient (Q1). The machine senses the ingredient has been spilled and interacts with the Blockchain requiring the registration of a new transaction, and providing needed information for maintenance and replenishment. The codes turn the reading process faster and avoid input errors. However, the complexity of the reading process can make this approach unfeasible and should be required to use these methods in conjunction with other technologies or only in a few steps of the process.

4.1.2. Radio Frequency Identification

There are many solutions in the literature applying RFID. In [121], the application of RFID technology in food supply chains and economic viability were discussed (Q1). However, the cost per tag can make the use of these technologies unfeasible when the granularity is high, and the product value is low. RFID has been applied to identify cattle and a Blockchain system supported by RFID tags was proposed to register its productive life information, such as production, sex, weight, origin, vaccine history, and so on [125] (Q1, Q2). RFID tags have been applied for the automatic identification of products and to reduce input error [88]. They can be integrated with IoT devices and product localization, avoiding theft and other illegal activities. RFID is generally applied for product batches, but QR codes can be added to a single package to enable consultation for consumers (Q1).

Signed and encrypted food codes can be stored in the RFID passive tag [85]. Food quality status and food identification can be collected and encrypted. Afterward, the encrypted code can be sent in transactions to the network. Based on RFID information the Proof-of-Object consensus was proposed in [86], where nodes can insert information on the Blockchain only if they prove cryptographically that they possess the object. The proof is made by a public cyber address registered on the Blockchain and a private address registered by RFID tags.

4.1.3. Near Field Communication

A NFC tag has the advantage of being readable by smartphones, improving consumers' usability. In [90] a combination of RFID and NFC tags was applied. RFID was adopted for node verification along the supply chain and NFC was deployed onto the packaging, for consumer usage. An Android application with this function was implemented in [94]. The app reads information of a tag and requests product information from the server or DLT. However, NFC's range is around 5-10 centimeters, which can be a limitation in some cases.

4.1.4. IoT devices

When the item monitoring must be done at the nearest possible of the products, a device composed of sensors and communication components is inserted in the batch (Q1). These devices can have relatively high costs and are usually adopted to identify batches of high-priced items. Possibly, the identification of a logistic resource is associated with the identification of the batch of products, e.g. a truck that transports milk [91, 126]. In these cases, the item identification can be made by the device. Thus, if necessary, each product can be identified prior to batch assembly and its information is associated with the IoT device. Each IoT device stores the code or the public key of the product batch it monitors and employs this identification when inserting transactions on the DLT (Q2).

4.2. Traceability and Immutability

Information about production, processing, and logistics, like the use of pesticides, and the addition of food preservatives and conditions during transport and storage, should be accessible to all actors in the FFSC. This information can be associated with the product by its identification code and providing a complete history of a product. Using the identification code, an actor can visualize the locate, temperature variations, and information about actors handling this product, for example, through the whole supply chain (Q1). Although DTs provide a way to follow the lifetime of a product (Q3), the solutions have been more concerned to represent the current state of the physical entity than keeping a data history. In this way, a DLT, like Blockchain, can support DT solutions, providing securely and efficiently data storage, data access, data sharing, and data authenticity (Q2) [92]. SCs can manage the creation and updating of DTs on the DLT [127].

To ensure that product data collected through sensors from each stage of the supply chain is legitimate and adheres to terms agreed by all parties involved in the system, a cloud platform has been adopted, and actors can access this data using a mobile application. However, centralized solutions have confidence and security problems. In a central repository, some party can alter the information by inserting unreal data for its own objectives. In this way, DLT has been studied and architectures models are proposed (Q2) [94]. Combining IoT technology and Blockchain, for example, the data collection credibility, security, and privacy are improved, and information is better exchanged (Q1, Q2) [128].

Table 7
DLTs implemented in literature to record FFSC transactions.

Papers	Implementation	Permission
[82, 87, 88, 90] [93, 96, 100]	Ethereum	Public
[96, 99, 101]	Ethereum	Private
[97]	Hyperledger Sawtooth	Permissioned
[99]	Hyperledger Sawtooth	Private
[103]	Hyperledger Fabric	Permissioned
[98]	Hyperledger Fabric	Private
[86, 95, 111]	Innovative proposals (Lighter consensus)	Public and Private

This data can be registered on a DLT, in an inter-ledger approach, in a cloud server, or in a combination of cloud and DLT, how Table 7 shows (Q2). Moreover, as mentioned before, the DLT can be public, private, permissioned, or a combination of different permissioned models. Although IoT devices' monitoring activity requires low battery usage, processing requirements to execute consensus on Blockchain can be a limitation in terms of energy consumption, leading some studies to propose lighter consensus operations for IoT. Using a combination of two or more DLTs, lighter consensus can be adopted while complex functionalities, like smart contracts, are still available. Another possibility is to use a conventional cloud server to store non-critical data and use the processing power of the server nodes to register important transactions on Blockchain, for example.

Ethereum has been the most employed Blockchain platform in the FFL proposals. A theoretical framework was proposed in [82] for building an end-to-end food traceability application integrating the Ethereum Blockchain and IoT devices exchanging GS1 message standards (Q1, Q2). An asset is described as a token, which is a digital representation of a physical asset, and all transactions involving this token are registered. SCs handled the creation of tokenized assets and nodes and the storage of data (Q6). A point or node has been adopted to represent a person, such as a farmer, or an IoT device. The Manager contract assigned roles and permissions for actors in the supply chain. The GS1 EPC Information Services (EPCIS) standard and Ethereum Blockchain were also adopted to design a decentralized system in [87]. Supported by RFID to improve food traceability (Q1, Q2), the proposal has provided collaborative management of on-chain (on the Blockchain) data, using Ethereum, and off-chain data, using the EPC network, to successfully reduce the amount of data in a single node. Moreover, sensitive business information has been protected by SCs, saving and managing food data and verifying the identity of enterprises.

SCs are employed to intermediate the relationship among the parties in the supply chain as described in [88]. It has been proposed a decentralized platform for maintaining perennial data, which is composed of a Server connecting nodes running on Ethereum software, an API-based Web3 tool to access Blockchain functionalities, and a Provider-consumer Software, which allows the user to sign transactions and interact with SCs (Q2, Q6). Actors can scan the RFID associated with products and update the details using the mobile app. A cloud server verifies, validates, and stores blocks of transactions. Similarly, the proposal presented in [93] has adopted SCs to register product transferring histories (Q2, Q6). Besides the management of the transactions among actors, an event response mechanism has been designed to verify their identities. Consumers and all nodes can join the network to maintain information flows. A Decentralized Application (DApp) has been built based on the Truffle framework for Ethereum Solidity language and Web3.js library. This DApp interacts with Ethereum Blockchain and it has been deployed on a test network TestRpc running in local memory.

A system for orphanage donation has been discussed in [100]. The system measures rice levels in different orphanages and makes information available to donors, providers, and suppliers. Donors can visualize the information using an application and request rice delivery for suppliers. A SC was implemented to send notifications to providers and suppliers, confirming payment and requesting the rice delivery (Q6). The raw data is stored on the providers' database and all transactions are registered securely and immutably (Q2) on the public Ethereum Blockchain. Using a private Ethereum Blockchain, a wine tracing system has been presented in [101]. An application for users to consult wine information scans a QR code and accesses a SC created for each product batch to view data, such as: grape yard, farm location, grapes characteristics, and cultivation in general (Q1, Q2). The application is brokered by an API for authentication and file storage.

Four architectures for food quality traceability in a multi-party business environment (Q2, Q6) were proposed in [96]. The architectures were also implemented based on Ethereum and evaluated, being: (i) a public ledger; (ii) a single shared ledger based on public DLT, but running only by members; (iii) one private ledger per pair of adjacent stages on supply chain, e.g. a private ledger between a producer and a manufacturer; and (iv) one private storage maintained by each member. Results show that the first scenario has prohibiting costs and delays, while the second is the least expensive solution. The third approach has positive effects on throughput and the costs are reasonable. Finally, the fourth is the simplest architecture and maximizes privacy, but does not solve data availability problems. A hybrid Cloud-Blockchain platform has been proposed in [102] to preserve FFSC actors' privacy. The solution improves data storage efficiency at the same time it provides relevant information to others stakeholders, such as: available products to trade and smart contracts to deal with business buildings.

Hyperledger is another Blockchain implementation commonly adopted in the literature proposals. In [97] the implementation of Blockchain technology in the eggs production and supply chain delivery system was explained. The authors discussed that traceability data of the eggs supply chain can help to attempt certification process requirements. A proof of concept was implemented using permissioned Hyperledger Sawtooth and Docker containers to deploy validators and custom SCs to support the insertion and visualization of transactions data (Q2). A proxy authentication server and a REST API have been implemented to provide different levels of access for devices, users, and applications. A permissioned Hyperledger Fabric Blockchain is applied in [103] to record user or sensor data in a tamper-proof way (Q1, Q2). The solution was proposed for traceability and the certification of the Extra Virgin Olive Oil (EVOO) supply chain, involving farmers, makers, couriers, and sellers. The authors have proposed and evaluated a mechanism for dynamic auto-tuning of Blockchain parameters to ensure a timed insertion of data on Blockchain.

A food delivery monitoring system was proposed in [98]. The system was composed of an IoT Logger, which determines the location and temperature of devices publishing these data over NFC and Bluetooth (Q3); Location Beacons, which broadcast an ID of a specific location (Q3); a Server App, which creates a semantic representation of the IoT Logger reports and save them on the Blockchain (Q2); a Private Blockchain network; and finally a Phone App that reads data from the IoT Logger, generate reports for customers and uploads data about delivery compliance (Q2). The Private Blockchain encompasses: (i) models to represent business entities; (ii) a model for a food delivery transaction; (iii) permissions to access data; and (iv) a RESTful API (Q1, Q2). To implement the system components and meet established requirements, a Puck.js device has been adopted. Also, the system encompasses a JAVA-based server app using the Apache Jena framework, a RESTful API implemented using the Spring Framework, the Hyperledger Composer project, and the Hyperledger Fabric.

A decentralized, Blockchain-based traceability solution for the food supply chain is proposed in [99]. The solution is composed of a REST API, which exposes system capabilities to other applications; a Controller that intermediates calls from API to Blockchain and vice versa; and a Blockchain that implements the business logic through SCs (Q2, Q6). All participants, including IoT devices, are registered users (Q1). A use-case was implemented aiming to meet all the requirements to establish farm-to-fork traceability using Ethereum and Hyperledger Sawtooth. It has been observed that Hyperledger Sawtooth has better performance.

A new Lightweight Consensus for IoT (LC4IoT) was proposed in [95]. It stored raw data on the cloud and associated transactions on a DLT (Q2). Transactions with actors' private information have been stored on a private Blockchain and transactions with general information, including product tracking, have been stored on a public Blockchain. An innovative proposal has also been presented in [86]. It implemented a consensus mechanism in which nodes cryptographically prove the property of physical objects using RFID (Q1, Q2). In [111] , a hybrid approach with both

Blockchain and Cloud development has been developed to enhance data storage efficiency, keeping DLT advantages (Q2). A Proof of Supply Chain Share (PoSCS) consensus, which mimics PoS, was proposed to mint or forge blocks by validators instead of miners. In this case, validators are stakeholders in the food supply chain.

4.3. Food Products Monitoring

Each kind of product in the FFSC is impacted by some environmental conditions, independently of its perishability. The methods of transport and warehousing can increase or decrease the product lifetime. Temperature changes can accelerate the bacterial growth in milk, for example. In fruits logistics, physical damages have the same result. For this reason, each logistics step must be monitored and the data obtained in this whole process must be available for consulting by end consumers. Temperature sensors have been applied to monitor the quality of fishes [104] or olives [103] during transportation. Considering these different characteristics, DTs of the products can be created, based on multiphysics and biochemical properties, and applied to control conditioning, e.g. during transport and warehousing, and to guide the management process (Q3, Q5) [106, 105, 129]. A DT must be as accurate as possible, however, the abstraction level and the minimum requirements to constitute a sufficient DT depend on its application.

Products monitoring can be implemented using IoT devices equipped with the required sensors and communication modules to transmit data to a cloud or some DLT. The sensors that have been applied to measure each of the most harmful environmental conditions in the FFSC are shown in Table 8. The best way to collect and transmit this data depends on the logistics process. The IoT devices can be installed in warehouses, carriers, or batches of products. Table 9 are shown the communication technologies that have been adopted in each of these approaches. The state of a product in a DT is updated by data collected using IoT devices.

For the use cases in which more precise monitoring is required, an IoT device is placed in a product batch. This independent IoT device follows the batch during all logistics processes and as discussed before, in this condition, the batch can be identified by the IoT device (Q1, Q3) [82]. Simple devices are employed for this application such as sensors and a simple communication module [130]. These can be independent and send information directly to some cloud, however, aiming to have lower-cost devices, they generally use the local network in the warehouse or carrier, or the mesh communication among the other batches' devices. Using reverse logistics to return the equipment downstream to the FFSC, more sophisticated sensors and communication is allowed than in a throwaway packaging solution.

These devices' batteries must be small-sized and last for years. Considering the amount of information and intervals relatively long to send data (about 30 minutes), devices stay in a sleep mode most of the time. In addition, battery life is usually not an issue, as shown in [131]. However, connecting a device directly to a DLT can be unfeasible, due to the power consumption for the required consensus mechanisms. In [95], IoT devices insert data on public/private Blockchain using a proxy node, associating data with products' ID (Q1, Q2, Q3). An oracle network has been designed to check the veracity of sensor data. Data can be mined after nodes, and oracles verified them, using a proposed lightweight consensus algorithm called LC4IoT.

Table 8
Sensors to collect environmental data in the FFSC [132].

Environmental Condition	Possible Sensor Mechanisms
Temperature	On-chip temperature-sensitive transistor Integrated semiconductor transducer Temperature-sensitive resistor Thermal couple Resistive Temperature Device (RTD)
Humidity	Humidity sensitive capacitor Humidity sensitive resistor Integrated humidity transducer
CO2	Infrared spectrum absorption detector
Oxygen	Electrochemical (oxidation-reduction)
Ethylene	Catalytic combustion of gases
H2S	Electrochemical (oxidation-reduction)
Vibration or Shock	Mechanical vibration switch Micro ball switch and counter Integrated accelerometer
Tilt	Earth magnetic and gravity sensor Integrated accelerometer
Light	Ambient light sensing photo diode
Location	GPS (Global Positioning System) Wireless communication technology

Table 9
Communication Technologies in the FFSC [69].

Approach	Technologies
Warehouse to DLT network	Can use wired connections with wide-band (like optical fiber)
Carrier or product batch to DLT network	SigFox LoRa WAN 3GPP NB-IoT Cellular (2G/3G/4G/5G) WiMAX Satellite
Product batch to warehouse or carrier	802.11a/c/b/g/n 802.11ah/p/af Bluetooth 6LoWPAN Z-Wave ZigBee RF Link NFC

4.4. Logistics Resources Monitoring

The warehouse or carrier monitoring level is generally sufficient to attempt FFL monitoring requirements. As discussed before, in these conditions, the batch can be identified by an ID associated with a tag (Q1). Two main logistics resources will be further considered in this paper. As a warehouse and a carrier have different mobility aspects, the communication technologies applied to transmit monitoring data are also different, how Table 9 shows. Similarly, as discussed before, a DT of a logistics resource also can be created for more accurate monitoring (Q4).

4.4.1. Warehouse monitoring

A warehouse can be a liquid tank, a grain silo, a pallet shed, a cold room, or any other environment. In some cases, it is required that the warehouses have mechanisms for acclimatization and environment control. Due to IoT devices that are fixed or with limited movement (to the size of the warehouse), warehouse-centric monitoring typically encompasses medium or short-range (less than 1 km) wireless radio communication technologies [94]. The battery of equipment can be easier recharged in this scenario. In some applications, wired communication and wired power sources are applied too.

When a product or a batch enters a warehouse, the first step is to identify it. This process is done using optical, RFID, or NFC readers while recognizing the tags applied on the product, batches, or carriers (Q1). Then, the environment data conditions in the warehouse begin to be associated on the DLT with the products (Q2, Q3), until they leave the location. The product identification process must be done in exit too. In [101] sensors deployed at grape yards, cellars, and warehouses can collect data about wine production, such as ambient temperature, humidity, and light, or barrel temperature and pressure.

Typically, warehouse monitored conditions are capacity, the position of products, gas concentration, temperature, humidity, or other environmental conditions (Q4). In [100] the implementation of a system for monitoring orphanages' rice stock levels has been presented. A load cell connected to a Raspberry Pi is placed in different orphanages, sending warehouse information to both a Cloud and a DLT, improving donors' visibility and facilitating donations. In [133] it has been presented a warehouse management system that employs unmanned aerial vehicles (UAVs) supported by DT and 5G. The entity warehouse was successfully represented by flight data and cargo information uploaded to Ali cloud through 5G communication. Instructions were sent by the DT platform to operate the UAV. In [107] the concentration of ethylene, CO2, and oxygen, temperature, humidity, and other conditions have been monitored to predict food shelf life and video cameras were employed to detect fire in warehouses, recording data on Blockchain for better transparency. A robotic drive-through system has been proposed in [110] for preparing and dispensing food and survival kits on a community scale. DTs of each component of the system were developed and used in simulation to examine system dynamics and performance.

4.4.2. Carrier monitoring

As in warehouses, the products or batches need to be identified before they enter or exit a carrier (Q1). The information collected by the carrier sensors is transmitted and associated, on the DLT, with the products carried (Q2, Q3). In this stage, the IoT devices are installed directly in vehicles or containers (Q4). Smaller logistics processes can use only trucks or trailers equipped with IoT devices, for example. However, only a container can be carried by diverse transporters during the process, like ships or trains. Therefore, containers in this case must have the necessary equipment installed [108].

The communication technologies in both cases need to have long ranges. The most adopted is the mobile network configuration. Notwithstanding, satellite approaches are also adopted in remote regions or where they are a viable option. In addition, when a product batch monitoring level is required, as discussed before in Subsection 4.3, the carrier can be employed as a gateway for external communications, rather than a sensor node, or in both cases. The power source in this stage can be a limitation. When fixed in vehicles, devices are connected to their electrical system. However, when equipment is placed in containers, a power source could not be easily accessed. In this case, a battery that supports sensor node and gateway configuration is required.

4.5. Decision support

Besides ambient control, tracking, and tracing requirements, the data collected in the logistics stages must be processed using data analysis methods to generate important information for decision making, hence improving the efficiency of the logistics operations. Based on information available about the environment through time it is possible to formulate a shelf life prediction [107] or a ML-based alarm system to help in taking preventive actions [126], avoiding food waste and loss, and delivering better quality products (Q5).

Among the factors that influence the degradation of food products are intrinsic, extrinsic, and implicit factors [72]. The intrinsic factors are related to products' characteristics, such as total and type of acidity, natural microflora, microbial counts, and so on; extrinsic factors are environmental conditions; and the implicit factors are contamination by microorganisms. Some of these factors can be monitored by the various kinds of sensors mentioned in Subsection 4.3. Using data collected about these factors and their combinations, mathematical models can be developed to make prevision about the degradation of many kinds of food products (Q5). Linear programming or Artificial Intelligence techniques apply these mathematical formulations to improve the precision of results and reduce computation time. For example, in [111] it has been presented a fuzzy logic approach for quality decay evaluation and shelf life adjustment, using temperature and humidity data.

Information about food quality degradation can generate alerts to operators or actuators systems, preventing food loss and attending to regulatory requirements (Q3). Integrated data about logistics resources can also be inputted in scheduling and routing problems, helping to decide which products should be delivered first and for which route (Q5). These alerts can be implemented as clauses in a SC [108] to ensure the accomplishment of transportation and warehousing conditions and apply fines and punishments, automatically. Typical product dispatch methods can be optimized to avoid waste. The FIFO (First In First Out) method disregards the products' shelf life. With the products' history and storage conditions data collected, a shelf life prediction is possible and FEFO (First Expired First Out) [134] or FPF (Freshest Products First) alternatives can be adopted to dispatch products, minimizing waste and cooling costs. Logistics vehicle scheduling optimization, based on CPS and optimization techniques, such as the Ant Colony algorithm can be employed [135]. Also, Genetic Algorithms (GAs), which are AI evolutionary approaches have also been applied to solve different problems in the perishable supply chain, such as the location-inventory-routing problem [136], design supply chain networks [137], and multi-period production-distribution planning [138].

Information collected during monitoring processes can be used to create a digital representation of routes, including the main characteristics of each route, such as mean and standard variation of temperature and vibrations. A pondered graph could be created and applied to take better routing decisions (Q5). In [109], a Blockchain-enabled Industrial Hemp Supply Chain (IHSC) to ensure food quality has been proposed and a preliminary simulation-based DT for the IHSC was developed to support the process learning and risk management. Most several scenarios of pandemic disruptions for food supply chains have been identified in [113] using a food retail supply chain DT. After modeling the DT, it can be used in a discrete-event simulation model to examine the operations and performance dynamics.

With a transparent information system, logistics service providers could improve their processes' efficiency. Farmers can inform their predictions for production or products in stock; distributors can offer their available logistics resources; and processors or retailers can share their demands. Using tracing data available on DLT, ML algorithms can be applied to predict demands [114] and improve actors' profits [115] (Q5, Q6). In [116], a reinforcement learning technique integrated with heuristic search method is applied to optimize self-driven vehicle routes based on management data registered on a Blockchain. Understanding and predicting actors' demands, as well as sharing logistics resources among the logistics providers, can help improve the efficiency of the FFL operation, e.g. routes would be traced according to the maximum utilization of resources, reducing the empty carrier travel (Q5).

4.6. Ecosystem for Logistics Providers

Whereas DLT is a technology highly coupled with FFL, due to the immutable traceability requirement, e-commercialization systems can be enabled, taking advantage of the financial transactions capabilities of DLTs (Q6). In [139], an agricultural products e-commerce based on Blockchain technology has been proposed. The system allows information visualization about products, market supply, and demands for all actors, in addition to providing feedback on inventory and logistics to producers, processors, and distributors. Actors can use DLT based system proposed in [117] to visualize product location and delivery time. SCs have been created to manage transactions among actors [93, 118]. Functions to register and update product status, and to buy, send, and receive products were implemented. These functions insert transactions and transfer funds among actors in adjacent steps of the chain, e.g. the supplier and the manufacturer. In [140], supply, bidding, trading, and utilization of SCs have been deployed on Ethereum Blockchain for the decentralized trading of food grains, using the Vickrey auction method to encourage trading among actors.

In addition, 4PL and 5PL providers can implement SCs to offer management and optimization services and 3PL can offer their services of packing, transportation, and warehousing (Q6). Traceability data can help to manage the accomplishment of service level agreements (SLAs) and key performance indicators (KPIs) for logistics services, including product information, shipment journeys, and freight details [111]. In [119], a framework has been proposed to majorly comprise Market Intelligence, using Big Data Analytics and ML to improve decision making; a Blockchain-based Food Supply Chain, using SCs to support business and cooperation among farmers; and a One-Stop Mobile App to improve the usability of the available functionalities. In [100], although financial transactions were not considered, a digital ecosystem has been proposed to facilitate communication to donors interested to help in supplying rice to orphanages, as well as to integrate rice suppliers. Using Ethereum Blockchain these actors can visualize the rice level in orphanage stocks and manage the buying and delivery of rice. In [120], it has been purposed Delish2Go, a P2P food delivery application to reduce the commission taken by food aggregators and bring transparency. SCs on KYC Blockchain were employed for restaurant and deliverers' identity verification, delivery service management, and possibly customer payment.

5. Open Challenges and Opportunities

Different approaches have been taken to attempt FFL, integrating several ICTs. However, it is noticed the distance between these solutions and the real applications, especially in development countries. Most of the employed technologies need more investigation about their limitations, integration with other technologies, and adoption in current FFL operations. Some challenges remain open and are discussed next.

5.1. Cost and complexity of solutions

There is a lack of capital and/or prepared labor force in the FFSC, from farms to consumers, especially in undeveloped countries, where much of the world's food production takes place. More reliable solutions must be implemented and evaluated to satisfy the needs of the actors, considering aspects, such as usability, flexibility, immutability, and cost. Poor processes and primitive technologies were identified as barriers to the adoption of the discussed solutions and technology upgrades as well as process standardization can be necessary [97]. However, given stakeholder resistance to change, the design decision for new solutions must consider current technology and processes and be incremental to them, as plug-and-play as possible.

RFID tags are one of the most efficient ways to identify products. Tags with integrated sensors can bring accurate monitoring with simple implementation. However, it's still infeasible for their use in low-price product batches, due to the tag costs. It is an open problem how to create cheaper and more sophisticated tags.

Due to the diversity of fresh food products on the FFSC, the processes of transport and storage and the monitoring methods are similarly diverse. There is a wide variety of sensors applied in approaches in the literature [141] and new ones have been developed [142]. However, creating cheaper and more precise electronic sensors is an open challenge.

5.2. Mobile communication challenges and trends

Technological solutions in the supply chain context is highly dependent on mobile communication, due to the need to collect and send data while nodes move through large geographic areas. Although latency and bandwidth are not problems, considering that data is normally sent in low frequency and short frames, mobility and range control must be considered. 5G and vehicular networks are trending technologies to support mobile communication in this way.

The 5G standard in mobile communication has been already tested and applied. The main improvements proposed are the wide range (about 50 km), mobility of devices (about 500 km/h), and connection density (1 million devices/km^2) [143]. These improvements benefit the application of IoT technology inthe supply chain directly, mainly on carrier and product batch motoring. The wide coverage range can reach highways and railroads, for example, from farms to retailers. The mobility allows continuous monitoring and the connection density can handle a load with multiple devices.

The logistics environment has high synergy with vehicular networks. These networks are mainly composed of vehicle nodes and have a lot of different characteristics from other wireless nodes. The logistics providers can use the infrastructure of carriers and warehouses to make their own network. These networks have highly dynamic topology and density, varying with the environment, such as a center of a city or a highway. Even though, the mobility of nodes is predictable, different from other ad-hoc networks, considering the road topology and layout. On another hand, nodes have sufficient energy and storage, because they are not limited in size and weight. Different from the IoT devices that usually must be handheld, the nodes in a vehicular network are cars, trucks, and so on. DT-assisted real-time traffic data prediction method can be proposed by analyzing the traffic flow and velocity data [144].

5.3. DLT issues

In FFL, data collected during the whole process help generate good decision insights and inform about real product conditions. However, the personal and business sensible information must be protected. Privacy of users, transactions, and SCs logic must be protected [145], especially with the integration with DTs. For example, a 3PL provider may provide a carrier DT publicly, showing information about capacity and price, but it is not in the company's interest to make its fuel consumption and other operation costs visible. Some inter-ledger solutions have been proposed for this problem, combining private, permissioned, and public DLTs, but such approaches need better performance and security evaluation. With a privacy-preserving-based inter-ledger, collaboration, coordination, and commercialization of resources and intelligence services among logistics actors can be stimulated.

Among the problems with DLT is data storage efficiency. Most solutions build architectures integrating different arrangements of conventional databases and DLT, storing only data hashes on DLT nodes [128]. Nevertheless, each record must be stored in each node of the network. Although some nodes can be light nodes that only store part of the ledger, e.g. last month's transactions, at least some nodes need to register the entire transaction history. In some cases, with a large number of transactions, memory usage may be impractical. Therefore, data perishability must be considered and evaluated to reduce the volume of records and keep the systems' reliability. Systems must be designed around policy to avoid irrelevant data insertion. For example, data about a batch of bananas does not need to remain registered on DLT for years. In this way, oracles can be employed to truthfully provide data outside the DLT, avoiding eternal registration on the ledger. On the other hand, data storage fragmentation and information clipping have been proposed to reduce the amount of data and improve system efficiency [87].

Due to Blockchain consensus operation, registering a block can be slow. The consensus mechanism, adopted to validate the inserted data, improves the data confidence, but it causes long delays. Thus, the frequency of registration requests and the volume of data must be as low as possible. Methods to choose what information should be on the Blockchain and the pre-processing of data and key indicators must be developed to lead the solutions in this context. Research about lighter consensus protocols, inter-ledger approaches, Oracles, or off-chain intermediary networks [85] also can help use data on DLTs with less overhead.

Considering the limitation of processing and battery of IoT devices, consensus must be lightweight. DLT solutions to this scenario have been evaluated, such as IOTA [146], and need more investigation. On other hand, edge nodes with better computational capabilities and power sources can be employed to process data from IoT devices and register on DLT. However, this approach can bring centralization problems. Oracles are a candidate solution for the intermediary problem. They are generally implemented as SCs to get data off the DLT, that is, data without consensus, and ensure the trust about it. However, as fake or incorrect data insertion by workers still can happen [111], data reliability and performance of oracles mechanisms must be evaluated. Self-verifying naming [147] have the potential to help with identification and integrity check. The application of this approach integrated with DLTs is a promissory research topic.

Besides the scalability, data security, and privacy problems, integration with existing legacy systems, collaboration among actors of the supply chain, and adoption of technological solutions for all supply chain stakeholders are pointed out as open challenges [111, 76]. Compliance only will be ensured if all parties involved follow the newly implemented policies and regulations. In this context, the design and implementation of fair and stable SCs is another subject of future work.

5.4. DTs and AI models

Digital Twins are widely employed in the industry in several segments. Some research has been done about DTs in logistics [6, 10]. However, there are few revisions and surveys about DT applied in logistics in general. This work provides a review of DT applications in logistics but focuses on FFL requirements, such as food products monitoring, tracking, and tracing. Therefore, one research opportunity is to survey state-of-the-art of DTs for general logistics processes, considering DTs' application in different supply chains, like distribution centers, ports, and rail operations, and identifying open challenges and opportunities for new research.

Artificial Intelligence techniques are widely applied to process data and have been supporting DTs building and operation, generating important information and insights, and making predictions in the FFSC. However, each kind of food product has specific characteristics and needs unique models. Therefore, a lot of work must be done to collect and format training data and to create and evaluate new models. These models can be sold in a digital marketplace to support actors' decision-making. Although the overestimated demand is pointed out by many authors as an impacting food waste cause, few integrative and synergistic solutions have been proposed in the literature. The biggest challenge here is the lack of access to accurate information about consumption. Because of this, precise models cannot be developed.

5.5. DT and DLT integration

The adoption of DTs technology in DLT-based systems needs to be better investigated, considering the clear synergy between IoT and DLT in the FFSC. Respecting the requirements of actors, DTs can be dynamically created and updated using SCs [127] and off-chain data, generated by IoT devices can be used. In addition, DLT is a tool for DT data management, providing secure data storage and sharing, avoiding man-in-the-middle attacks and tampering.

However, some challenges emerge from this integration. Due to insertion transaction costs and delays, data updating must be performed only when important events happened or with long time intervals, which makes monitoring far from being real-time. With cheaper or free transaction costs, e.g. offered by IOTA, and more efficient consensus protocols, this problem is mitigated. On other hand, the DLT transparency problem also needs to be considered to preserve the private DT data.

6. Conclusion

A review of applications integrating IoT, AI, DTs, DLTs, and SCs has been performed in this work. Information flow in the FFSC was analyzed and detailed. Many IoT solutions related to monitoring the logistics processes in the FFSC have been found in literature aiming to decrease waste and improve FFSC efficiency. DTs solutions have been improving the accuracy of products' and processes' digital representation and supporting simulation and optimization. DLT is being applied to bring transparency and trust among actors, preserving the security and privacy of transactions. SCs bring security and make it easier to provide logistics resources and services.

Among the open issues in research, there is the data ownership and privacy of farmers, industries, and distributors. The cost of the identifiers in large-scale solutions is also presented as a limitation. Storage usage and registration efficiency have been pointed out as DLT issues. DT and intelligent models to help in the FFSC process must be proposed and evaluated. Emerging communication technologies, like the 5G and Vehicular Networks, promise to lead the rise in logistics research.

The proposal and evaluation of a new architecture to integrate DT and DLT for FFL is a possible future work. The integration of these technologies has the potential to improve several processes' efficiency, especially on FFL, and needs better investigation. In addition, it is necessary to explore the business supporting capabilities of DLTs and SCs, by creating and evaluating DLT-based digital marketplaces. DTs can be employed to improve the visualization of physical products or resources involved in services' operations and provide a stronger connection for data exchange between products and logistics resources.

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