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ORIGINAL RESEARCH

An orchestrated IoT-based blockchain system to foster innovation in agritech

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Abstract

Agritech uses advanced technologies to boost the efficiency, sustainability, and productivity of farming. The Internet of Things (IoT) in agriculture has brought sensors and networked technology to gather and analyse environmental and crop data, enabling precision farming that optimises resource usage and increases yields. Yet, current agricultural methods suffer from unsecured and decentralised data management, causing inefficiencies and complicating traceability across the supply chain. The integration of IoT with blockchain technology is seen as a promising solution to enhance data-driven agriculture. Blockchain provides a secure, decentralised, and transparent ledger that enhances data integrity, reduces fraud, and improves traceability, which complements IoT applications. The authors detail the development of an innovative system that orchestrates IoT and blockchain technologies to facilitate the adoption of new technologies in agriculture and overcomes the lacked of comprehensive data connectivity. It outlines a conceptual framework and its preliminary empirical implementation. The system consists of three integrated layers: the IoT layer, which creates digital twins of field crops; the blockchain layer, which secures and manages data from the field and external stakeholders for dynamic applications such as track and tracing; and the orchestration layer, which fuses physical and digital data to optimise business models, enhance supply chain productivity, and support governmental policy-making, thereby improving field productivity and food sector innovation.

KEYWORDS
customer services, data analysis, decision making, intelligent manufacturing systems, networked control systems, ubiquitous computing

1 | INTRODUCTION

Agriculture has always been a driver in technology development for almost 12,000 years. Since the Neolithic Revolution, humans have developed tools and techniques to master the craft of domesticating plants and animals, aiming for more productivity and quality in crops [1]. The relentless quest for better food and productivity has historically sparked innovation on many fronts. From biotechnological advances [2] to the use of aerospace technologies [3], humans have evolved due to in significant part by applying new tools and methods to manage scarce resources such as land, water, and energy for food production.

Current technological developments in agriculture continue this quest by applying a multitude of innovative systems, in particular, sensors and data management [4]. Combined, this new approach to farming, merging multiple technologies and methods, can be conceptualised under the rubric 'Agritech'. The Agritech sector has consolidated its importance recently, growing 24% per year, reaching approximately eight billion dollars in venture capital investment worldwide (Figure 1) [5].

In particular, Internet of Things (IoT), wireless networks, and new computational methods to process data, such as Artificial Intelligence (AI) and Distributed Ledger Technologies *aka* Blockchain, have the potential to positively impact agriculture in the 21st century. The correct orchestration of

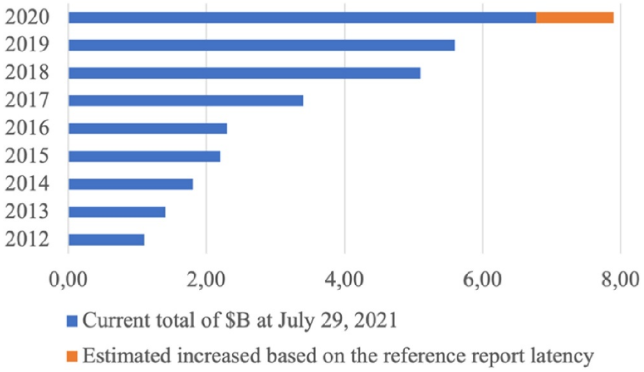


FIGURE 1 Annual Financings from 2012 to 2020. Data from [5]. Graph prepared by the authors.

crop production processes and new technologies can significantly improve field productivity while innovating in the food sector. Technologies such as smart-crop monitoring, drone farming, smart-livestock monitoring, autonomous farming, smart building and equipment management could generate a total positive worldwide GDP impact of more than 120 billion dollars by 2030 [6].

In this paper, we propose an innovative system by orchestrating IoT and Blockchain to operationalise the adoption of new technologies in agriculture. The systems builds-up in three cohesive, additive layers. The IoT layer creates digital twins of field crops by applying a sensors fusion approach using a combination of wireless technologies, sensors, or cameras, among other technologies. The blockchain layer connects and makes sense of data from the field and external stakeholders that belong to the agriculture supply chain, allowing for a dynamic data use with applications such as tracking and trace, dynamic pricing and logistics etc. The orchestration layer integrates both the physical field (crops) and its digital twin (data), allowing the emergence of information and knowledge to improve productivity across the supply chain, optimised business models in the industry, and the possibility for governments to formulate better policies for the sector, optimising the application of public funds. A cohesive, integrated use of technologies is expected to create better food at lower prices.

The rest of the paper is organised as follows. Section 2 explains how the pursuit of better productivity in agriculture and the application of effectuation heuristics can serve as boosters for innovation adoption in the sector. Section 3 presents a brief introduction to IoT and blockchain technologies. Section 4 describes our integrated system and identifies some challenges to be faced for the particular case of indoor and urban farming. The most significant findings are summarised in the conclusion.

2 | AGRITECH, INNOVATION, AND EFFECTUATION

The creation of new ventures is an uncertain initiative. Innovators and entrepreneurs create original products and services to reduce existing information asymmetries and generate value while solving a problem faced by one or many individuals (Donaldson, 1934; Knight, 1921; Sarasvathy, 2001; Schumpeter, 1934; Tasic & Andreassi, 2008). In brief, the innovation process and expertise typically consist of non-predictive control heuristics, organised under the concept of effectuation (Sarasvathy, 2009). While forming a new service or product, the effectual principles are applied by innovators and expert entrepreneurs to address uncertainties. These principles are

- Bird-in-hand principle: They build a new venture not necessarily with a goal in mind but with the most basic resources and means they have at hand, who they are, what they know, and whom they know. From that starting point, they start imagining possibilities.
- Affordable loss principle: They do not place large bets with the expectation of high returns. Instead, they limit risk by understanding what they can afford to lose at each step in creating a new venture. By adopting this approach, they select actions and goals with upsides even if downsides happen in the outcome.
- Crazy quilt principle: They reduce uncertainty by partnering with self-selecting stakeholders. These partners and stakeholders join the venture creation process without any particular predetermined goal. Instead, they make initial commitments to shape the goals of the new venture and co-create a new market for it.
- Lemonade principle: They embrace and leverage contingencies and surprises instead of rejecting them. By doing so, they interpret potential bad outcomes as clues and insights to iterate and create new products, services, and markets. They make lemonade when life throws them lemons.
- Pilot in the plane: They focus on actions within their control instead of relying on trends or inevitable outcomes. They assume the future is not found or predicted, but it is made through human action.

These principles imply a high likelihood of innovation while keeping potential losses under control and undermine the socially accepted relationship between risk and reward. A case in point of early attempts to innovate by using these principles is shown in Ref. [7]. The authors studied different capabilities that boost agility in international high-tech SMEs. They found out that four out of the identified nine capabilities, that is, flexibility, speed, responsiveness, and decision-making capabilities, refer to effectuation logic. Another research where effectuation is employed is [8]. In that work, the authors claimed that small-scale farmers can share a similar set of heuristics as proposed by the effectuation theory, which in turn can be grouped into five individual archetypes (accumulator, risk outsourcer, imitator, integrator, and improver). There is another interesting work that addresses effectuation to bridge the innovation gap, in this case for the Biomass-to-Liquid market [9]. The authors concluded that effectuation processes need to be enabled by bringing together market actors from different fields, alluding to the effectuation logic where the effectuator assembles enough stakeholders to create a sense of commitments through an effectual network able to translate present realities into new markets.

3 | TECHNOLOGIES: IOT AND BLOCKCHAIN

This section summarises the most important features of blockchain and IoT and some recent research works bringing these technologies to the agriculture sector.

3.1 | Blockchain

In short, a blockchain can be understood as a shared, distributed, fault-tolerant database (*ddbb*) and a network of nodes (e.g. PCs) that operates on it. In this case, the database is composed of data structures called *blocks*. Each block usually contains several verified transactions, a timestamp indicating the instant of creation of that block and a random number (*nonce*) for cryptographic operations. All these blocks are *chained*; the reason is that each block includes a hash value of its predecessor block that acts as a linking element. A hash H is a mathematical one-way function; given x, we can calculate its hash $h = \mathrm{H}(x)$, but given h is computationally intractable to obtain x. Besides, the probability that two inputs x_1 and x_2 generate the same hash h is very low, approximately 2^{-n}, where n is the length of the hash h in bits. Therefore, hashes are employed usually for checking integrity to verify if the original input x has been modified without authorisation. Because each block contains a hash of the previous block, changing the content of a block b that occupies the position i in a chain of size m blocks ($m >> i$) would imply modifying the content of all subsequent blocks, that is, in this case, $m - i$ blocks should be modified. This is also the reason why a blockchain only allows data aggregation and there are no modification or deletion actions.

On the other hand, the blockchain network consists of *nodes*, devices with connectivity between them through a communication network that maintain the blockchain in a distributed manner. All nodes have a copy of the blockchain, all its blocks, but no node has complete control over it. When a blockchain user needs to interact with another user, for instance, to register a transaction between them, what they do is sending their transaction to the blockchain network. Several nodes in the network will check if the transaction is valid and then they will try to build a new block including the data of this transaction through a process called *mining*. When a node (*miner*) is able to create a new block, it will communicate to all the other nodes that a new block has been added to the blockchain. Then, these other nodes will verify the validity of this new block that has become the latest in the blockchain by checking some cryptographic values. If a node, independently, concludes that the block is valid, then the block is added to the blockchain, otherwise the block is discarded. Both transactions and blocks are digitally signed; therefore, they cannot be reversed or denied in the future, a feature that is called non-repudiation. Acting in this way, blockchain technology allows communicating parties to interact in the absence of a trusted third party. The interactions are recorded on the blockchain, providing the desired security requirements.

Depending on the different levels of permission to insert data or to access the recorded information, a blockchain is categorised as (i) public (e.g. Bitcoin or Ethereum), (ii) consortium-based (e.g. Ripple), or (iii) private (e.g. Hyperledger). In a public blockchain, virtually anyone can participate, and each participant is usually anonymous. In this context, there can be no more trust than the fact that from a certain depth, the blockchain is immutable. However, private blockchains operate the blockchain among a set of known, identified participants operating under a governance model that produces a certain degree of trust. This type of blockchain offers us a way to secure interactions between a group of entities that have a common goal but may not fully trust each other. Smart contracts were introduced in the third generation of blockchains. A smart contract is a programmable contract or agreement that is verified by everyone in the network; therefore, it forces both parties of the communication to strictly follow certain rules. With the third generation, the capabilities of blockchain were significantly enhanced, increasing the interest of the scientific community and industry for its application in other areas.

3.2 | Internet of Things

New communication technologies are boosting connectivity. The sometimes desired ubiquity is closer and closer and a good example can be found with IoT [10]. A complete IoT system is made of three layers. The first layer is composed of small physical devices, usually with light computational capabilities and energy constraints, which are able to communicate with other devices. Communication can consist only in sending collected data with the use of sensors (temperature, humidity, acceleration, presence, vital constants, etc.), cameras (images and video), or any similar device, or to send the collected data and receive some data back. Thus, the main two elements of this first layer are the so-called IoT devices (e.g. wearables, development boards, etc.) and a communication protocol that enables the data exchange (e.g. WiFi, Bluetooth, LoRa, Sigfox, Narroband-IoT, ZigBee, 5G, etc.). The second layer is responsible for receiving the collected data and processing it. This task is sometimes carried out in the cloud, with virtual machines or dedicated servers, and other times is done with on the premise infrastructure. Data processing often involves the use of machine learning techniques to infer as much information as possible. Finally, the third layer interacts with the users, and common tasks are visualisation, knowledge creation, decision making, and actioning the execution of consequent tasks.

The success of the deployment of IoT-based systems in agriculture is reflected in the related literature. To summarise the IoT impact on agriculture, we can mention five use cases with the potential to transform this industry: smart crop monitoring to optimise crop growth and resource utilisation [11], drone farming to improve monitoring and enable remote interventions [12], smart livestock monitoring for forecasting animals' health [13], autonomous farming machinery to reduce costs [14], and smart building and equipment management for more efficient maintenance.

3.3 | Embracing IoT and blockchain in agriculture

IoT for agriculture is deeply reviewed in Ref. [15]. The authors present a survey on IoT technologies in smart agriculture, highlighting their role in advancing farming practices. It covers the utilisation of various IoT devices and sensors, such as soil moisture sensors and drones, for collecting critical data on crop health and environmental conditions. The survey emphasises the importance of big data analytics in analysing the collected data to offer actionable insights, thereby aiding in precise farming, resource management, and yield enhancement. It also addresses challenges such as interoperability, data privacy, and the necessity for strong network infrastructures, while suggesting future advancements such as the use of AI-driven predictive models to further improve agricultural outcomes.

The food supply-chain industry is at the forefront of IoT adoption, and the use of sensors allow to automate the (real-time) data collection at the site. Provenance, traceability, and transparency are key factors of food logistics and are becoming ever more important with advancing food technologies and globalisation. Two important challenges in the current supply chain are the identification of origin of health outbreaks and the dismal low efficiency in spite of significant food spoilage/waste [16, 17]. These issues could be addressed by tracking and tracing the information of the supply chain using an IoT-based monitoring of all stages of food logistics, which includes pre- and post-harvesting, storage, processing, distribution, sale, and consumption [18]. However, the dynamic nature of the agricultural supply chain and the participation of different intermediaries increase tremendously the complexity of these tasks. Several authors have identified that the current practice of traceability in this context largely suffers from data fragmentation and centralised controls, being exposed to management and data modification, and the exchange of information between stages is time-consuming and difficult [19]. In this context, blockchain is a disruptive technology whose recent developments can contribute with a practical and robust solution to track and trace agricultural products without the need for a trusted centralised authority.

The International Telecommunication Union (ITU) and FAO recently published a study showing the increasing impact of blockchains on several areas of agricultural sectors, their possibilities and risks [20]. From the related scientific literature, we can observe that this approach is at a very early development stage, though. A good comprehensive study on blockchain-based agricultural applications and current innovations to promote this type of techniques can be found in Ref. [21]. Specifically for the agri-food supply chain, the work introduced in Ref. [19] studies how to employ blockchain and Ethereum smart contracts to track, efficiently follow, and enable seamless integration of business transactions and workflows for the case of soybeans. Similarly, in Ref. [17], an end-to-end solution for the agri-food supply chain is presented, and the authors evaluate their blockchain proposal in terms of traceability, trade, delivery, and reputation. Another example of the integration of IoT and blockchain can be found in Ref. [22]. It outlines a model that automates various agricultural processes using smart codes to minimise risks and errors, thereby increasing the productivity of agro-based supply chains. The model utilises IoT sensors for environmental data collection and blockchain for secure data storage, with Java smart contracts automating decision-making tasks. This integration aims to address issues such as data silos, security vulnerabilities, lack of transparency, and inefficient procedures that are common in centralised databases within the agricultural sector enhancing food security.

The integration of IoT and blockchain in the supply chain is also addressed in Ref. [23], highlighting issues with data quality that blockchain alone does not solve. It introduces a framework prioritising “common knowledge” over absolute data accuracy to ensure product authenticity between countries. The authors challenged the traditional use of these technologies merely for tracking, advocating instead for their role in shaping future behaviours and outcomes via cryptoeconomics. The study calls for a shift towards using IoT and blockchain to actively enhance supply chain outcomes, marking a significant move towards more efficient, transparent, and integrity-driven food supply chains. In this sense, the authors in Ref. [24] study Privacy-Preserving Blockchain Systems (PPBS), highlighting their potential to revolutionise smart agriculture by ensuring data privacy. They propose a new framework called Privacy Preserving Smart Agriculture Framework (PPSAF), aimed explicitly at addressing privacy issues in smart agriculture. This framework is central for secure data management in agricultural contexts, emphasising the importance of privacy-preserving techniques in blockchain applications to enhance trust and security in smart farming practices.

The work presented in Ref. [25] highlights a novel integration of IoT and blockchain to foster a transparent, efficient agricultural ecosystem. It proposes a model leveraging IoT sensors for environmental and agricultural monitoring, with blockchain ensuring secure data management and traceability from planting to consumption. This model, aimed at facilitating informed consumer decisions and sustainable farming practices, utilises the Low Energy Adaptive Clustering Hierarchy (LEACH) protocol to optimise energy use and network stability, illustrating a commitment to sustainability and consumer empowerment within the realm of smart agriculture.

Food security utilising blockchain and IoT for fostering sustainable smart agricultural practices is studied in Ref. [26]. The paper examines the integration of both technologies in agriculture, focusing on using blockchain for tracking crop production and IoT sensors for real-time monitoring of agricultural conditions. This integration aims to make farming more data-driven, optimising resource usage, enhancing crop yields, and providing traceability from farm to fork. The model addresses environmental issues such as soil degradation and pollution by reducing excessive farming inputs and improves food security by streamlining supply chains and minimising waste. Highlighting the transformative impact of blockchain and IoT in agriculture, the paper calls for further research into scalability, economic viability, and environmental impact to maximise the benefits of smart agriculture worldwide.

The authors in Ref. [27] propose a novel framework to enhance traceability in agricultural supply chains using blockchain technology, Self-Sovereign Identity (SSI), and Decentralised Key Management Systems (DKMS). Focusing on addressing the challenges of tracing agricultural products' origins in supply chains taking into account the limitations of centralised architectures, this framework aims to provide a trusted service for tracking agricultural food products without using IoT. By integrating SSI and DKMS on the Fantom blockchain network, the model ensures faster, cost-effective transactions and enhances the authenticity, integrity, and confidentiality of the supply chain's data management. The implementation shows that the Fantom-based blockchain network significantly outperforms others in terms of transaction and verification timing, suggesting a scalable and secure solution for agricultural product traceability that could revolutionise supply chain management by making it more transparent, reliable, and efficient.

Another approach to enhance smart agriculture within the context of blockchain is the combination with eXplanaible AI (XAI) [28]. This work emphasises blockchain's role in creating a transparent, secure platform for recording agricultural data, and XAI's potential to make AI-driven agricultural decisions more understandable and trustworthy. The study provides a bibliometric analysis to explore the integration of these technologies in smart agriculture and highlights the importance of such integration in improving supply chain transparency, ensuring food safety, optimising resource use, and supporting sustainable farming practices.

An in-depth examination of the security and privacy issues in IoT-based agriculture is presented in Ref. [29], proposing a four-tier architecture model to enhance security and privacy through blockchain technology. It categorises threat models into attacks against privacy, authentication, confidentiality, availability, and integrity, offering a comprehensive classification and analysis of state-of-the-art methods for securing and preserving privacy in IoT applications within agriculture. The paper emphasises the potential of blockchain and consensus algorithms such as Practical Byzantine Fault Tolerance (PBFT) to address these challenges, proposing solutions for secure, privacy-preserving green IoT-based agriculture. Also, economic implications of the combination of IoT and blockchain have been analysed in Ref. [30]. The paper presents a comprehensive examination of how blockchain technology can revolutionise IoT payment systems and marketplaces. It discusses the potential of blockchain to address the challenges of interoperability, security, and privacy in the IoT ecosystem. The technical hurdles in realising IoT payments and marketplaces, such as poor interoperability, resource constraints, and security vulnerabilities, are discussed. It argues that blockchain, with its inherent traits such as decentralisation, traceability, and immutability, offers promising solutions to these challenges, facilitating the creation of a trusted IoT marketplace without the need for central authorities.

Finally, there are also some initiatives around the world that follow this approach, such as the partnership between Dole, Unilever, and Walmart with IBM in their FoodTrust initiative [31]. Nevertheless, research is still needed to solve several challenges that the use of blockchain rises, and that can be mainly categorized in i) scalability issues when integrating with data intensive technology, such as IoT, ii) integration with existing legacy systems and standardisation, and iii) security and privacy. These challenges could be addressed by hybridisation with other systems such as IPFS (InterPlanetary File System) or edge computing [32], applying new security methods for data privacy [33], or adopting new standards for food logistics related to data collection, representation, storage, and access control. As an example, the IEEE Standards Association (IEEE SA) has recently launched a working group for IEEE P2418.3™—Standard for the Framework of Distributed Ledger Technology (DLT) Use in Agriculture.

4 | AN ORCHESTRATED INNOVATION SYSTEM IN AGRITECH

Based on the current state of the art, we propose an integrated system to operationalise the adoption of new technologies in agriculture and cope with the identified challenges. The system lies on three layers, namely the IoT layer, the blockchain layer, and the orchestration layer. In general, the relationship among these layers is symbiotic and sequential, as described in Table 1. The IoT layer captures and provides real-time data, the blockchain layer secures this data and ensures its integrity, and the orchestration layer utilises this information to drive innovation and efficiency in agricultural practices. This structured interaction allows for a highly integrated approach to managing agricultural data, enhancing productivity, and fostering innovation in the sector.

In order to provide a comprehensive understanding of the system, we will apply it to an urban farming research project and will showcase its adaption to this system. The urban farming setting has the goal of optimising the use of hydroponic cascade systems in urban agriculture to crop autochthonous vegetables [34], for example, by diminishing the nutrient load closing nutrient cycles and using compost and its extracts with salt-tolerant vegetables to qualify the nutritional implications of cascade systems, whilst using friendly packaging for Km0 distribution [35]. Next sections explain the three layers in detail.

4.1 | The IoT layer

First, the IoT layer is in charge of creating a digital version of the field or the greenhouse, for example, in our case, we are working with vertical farming in urban farming. This digital version can be defined as a digital equivalent of the real field that emulates its behaviour and its states and can be observed

TABLE 1 The proposed system's layers.

Layer	Mission	Function	Relation to the other layers
IoT	Foundation	It is responsible for creating digital versions of physical fields or greenhouses, essentially forming digital twins. It involves the use of various IoT devices and sensors to collect data about the physical state of crops, soil conditions, climate variables etc.	The data collected by the IoT layer serves as the foundational input for the blockchain layer. It ensures that accurate, real-time data about the physical conditions of agricultural entities are recorded and made available for further processing and analysis
Blockchain	Data security and sharing	This layer secures, stores, and manages the data collected by the IoT layer. It ensures the integrity, traceability, and accessibility of agricultural data, making it resistant to unauthorised modifications and fostering trust among all stakeholders in the supply chain.	Data from the IoT layer is fed into the blockchain layer, where it is securely recorded. This layer acts as a bridge between the raw data collected from physical environments and the decision-making processes facilitated by the orchestration layer. It also ensures that data sharing across different stakeholders is secure and transparent.
Orchestrator	Innovation	It integrates both the physical and digital (data) realms, enabling optimised business models, knowledge creation, and the formulation of effective policies for the agricultural sector. It utilises the data secured by the blockchain layer to facilitate dynamic applications such as track and trace, dynamic pricing, logistics etc.	This layer brings together the IoT and blockchain layers, orchestrating the use of data for actionable insights and decision-making. It leverages the secure and immutable data provided by the blockchain layer, along with the real-time, contextual data from the IoT layer, to enable comprehensive management and optimisation of agricultural practices.

from a remote (mobile/virtual) device. Besides, we could expand its funcionality and see it as a digital twin, defined as 'a virtual instance of a physical system (twin) that is continually updated with the latter's performance, maintenance, and health status data throughout the physical system's life cycle' [36]. The use of a digital twin allows decoupling data aspects of farm procedures from physical flows, detaching the need of physical proximity, and facilitating the remote control and execution of particular farm tasks, including monitorization and coordination [37].

For our use case, this IoT layer is firstly designed to capture basic parameters included in Table 2. Also, there are some manual inputs, identified as such in Table 2, which can be incorporated via web forms or specifically-design apps for mobile devices. Collections means for IoT can (and should) be varied. Table 3 enumerates different IoT telecommunication technologies for data collection. As a preliminary approach, we use QR codes in our use case. In an Ubuntu 20.04.5 server, we installed and configure a web server with Apache and an SQL database to collect the data through web forms using PHP and *javascript*. *phpCAS* library was employed for users' authentication. After inserting the data, the web application creates a unique QR code for each product using the library *endroid* QR code generator. These QR codes are printed in RFID tags that can be automatically read when corresponding, for example, to calculate the transport journey time. In addition, QR codes can be read with any mobile device taking the user to a web page showing the product data. More details about these data are shown in Section 4.2. It is expected that the collected data will have a different use depending on the stakeholder. Therefore, these data have been classified as public when it is available for the consumers and sellers and private otherwise (e.g. farmers, governmental entities, etc.). In summary, the IoT layer would be able to create digital twins of field crops, which can be recreated, by applying a sensors fusion approach using a combination of wireless technologies, sensors or cameras, among other technologies.

4.2 | The blockchain layer

Second, the blockchain layer connects and makes sense of data from the field and external stakeholders that belong to the agriculture supply chain, allowing for a dynamic data use with applications such as tracking and trace or dynamic pricing and logistics (see Figure 2). In order to select the best blockchain technology, we propose to focus on three factors: (i) scalability, (ii) integration with legacy systems, and (iii) security and privacy. With this aim, we propose the use of a private-shared blockchain. This storage system offers us scalability and sustainability in the face of an increase in data to be stored while maintaining its integrity. The highest level of security is achieved by being able to incorporate into the private-shared blockchain only those data that are agreed by stakeholders and those that are mandatory by regulatory bodies or current legislation. In addition, collected data that is classified as private will be stored encrypted to guarantee its privacy, whilst data catalogued as partially public is accessible via control access.

In its application to our case, we have chosen hyperledger fabric [38] as the blockchain technology. It is an open source solution designed for enterprise use as a permissioned distributed ledger. Among its advantages, we highlight a wide technical community, a configurable and highly modular architecture, and smart contracts can be developed in several well-known programming languages (e.g. Java). Because it is permissioned, the participants are known to each other and even though they might fully trust each other, they agree on a governance model in the form of a framework or a legal agreement. In this type of blockchains, a Byzantine Dault Tolerant (BFT) consensus protocol can be employed with the benefit of hugely decreasing computational requirements (no need for mining). It is also worth noting that all actions carried out in this blockchain are indentifiable, that is, either requesting transactions to be performed, deploying a smart contract, modifying the configuration, or even reading queries following

TABLE 2 Collected data.

Phase	Parameter	Type of input IoT/manual	Examples	Type of information (private/public)
Preparation	Greenhouse details	Manual	"Estación experimental Agroalimentaria Tomás Ferro" (37.686376, −0.950268) of the "Universidad Politécnica de Cartagena" (Murcia, Spain)	Public
	Crop type	Manual	Soil or soilless	Public
	Gutter (material and dimensions.)	Manual	Cell plastic trays for seeding and metal gutters of pyramidal trunk cross-section (1.0/0.15/0.12/0.11 m in length/upper width/lower width/height)	Private
	Fertilisation, substrate, and growing media	Manual/IoT	Physico-chemical and chemical characteristics, physical characteristics, and Agro-industrial compost.	Partially public
Seeding	Species	Manual	Rocket (*Diplotaxis tenuifolia (L.) DC.*)	Public
	Irrigation system	IoT	Types of sensor, amount of water applied, humidity, drainage etc.	Partially public
	Fertigation	IoT/Manual	Initial values and subsequent characterisation	Private
	Lighting	IoT	Type of sensor, daily light integral (mol/m2/d).	Private
	Temperature	IoT	Type of sensor and air temperature (min/max/avg).	Private
	Sowing date	Manual	Date, hour	Public
	Transplantation date	Manual	Date, hour	Private
	Transplantation details	IoT/Manual	Density (seedlings stage, plants/m^2)	Private
Harvesting	Number of harvets	Manual	2	Public
	Harvesting date	Manual	Date, hour	Public
	Growth analysis	IoT/Manual	Leaves weight, leaves area, and dry weight	Private
	Phytochemical Analyses	Manual	Glucosinolates and (Poly)phenols Extraction, Glucosinolates and Phenolic Compounds, Vitamin C and Antioxidants content	Partially public
Post harvesting processing	Disinfection	Manual	Types of sanitisation process and products	Private
	Storage	Manual	Duration, temperature,	Partially public
Packaging	Material	Manual	Polypropylene (OPP), poly lactic acid (PLA)	Public
	Recyclability	Manual	Biodegradable	Public
Transportation	Origin/Destination	IoT	From "Estación experimental Agroalimentaria Tomás Ferro" to restaurant or local market (GPS locations) or RFID reading	Public
	Transport means	Manual	Electric vehicle	Public
	Duration	IoT	Using RFID at the origin and destination	Public

an endorsement policy previously agreed by all participants; so the origin of any action can be identified unambiguously providing non-repudiation.

We have deployed a hyperledger fabric network (Fabric v2.2) using *node.js* and is composed by three peer organisations (emulating the farmer, distributor, and retailer). The application, for interaction between the blockchain and the peers, has been developed using PHP, *node.js*, HTML, and API RESTful technologies. The network configuration carried out in the Ubuntu 20.04.5 server emulates three distinct peer organisations: farmer, distributor, and retailer. Each organisation is a separate entity in the network with specific roles and permissions. The network utilises Docker containers to host the peers, orderers, and Certificate Authorities (CA) for each organisation. Hyperledger Fabric uses a Public Key Infrastructure (PKI) to verify the identity of network participants. Each organisation in the network operates its Certificate Authority (CA), responsible for issuing and managing digital certificates. This setup ensures that all transactions and communications within the network are secure and authenticated.

In hyperledger, channels are private subnets of communication between specific network members, offering a way to conduct private and confidential transactions. In this setup, a channel is created for transactions among the three peer organisations, ensuring that only these parties can access transaction data related to the fresh vegetable products. Another important concept in Hyperledger Fabric is chaincode. It is a piece of code that encapsulates the business logic of the

TABLE 3 IoT collection means and connectivity.

Technology	Communication range	Degree of implementation in agriculture	Characteristics
QR codes	Reading camera viewing range	High	Identificacion, reading or writing data (into another location using, for instance, web applications), for example, registering and reading dates.
RFID	Short range up to 2 m for frequencies <1 GHz	Medium	Identification, small data storage&exchange, efficient device-to-device connectivity, for example, registering and reading dates.
Bluetooth low energy (BLE)	Short range up to 10 m	High	Identification, small data storage&exchange, efficient device-to-device connectivity, for example, register and read lighting data.
NB-IoT	Long range up to 15 km	Medium	Long Range wide area network (LPWAN). It supports a considerable density of IoT devices. Few data without duty cycle limits. Licenced technology using a licenced spectrum (mobile network operators).
LoRa	Long range up to 30 km	Medium	LPWAN. It supports a considerable density of IoT devices. Few data with a duty cycle <1%. Open protocol using an unlicensed spectrum.
WiFi 6/7	Medium range up to 50 m	High	Improved speed, device density, and increased device efficiency. It serves as a connection to the Internet for QR, RFID, and BLE.
5G	Medium range up to 600 m for mmWave	Low	Low latency, high speed, high reliability, high energy efficiency,[a] and ultra-high connection density.[a]
Low Earth Orbit (LEO)	Ultra long range	Low	Global coverage via low earth orbit satellites at an altitude <1000 km (could be as low as 160 km) with significant reduced latency compared to other satellite solutions.

Note: These technologies need an additional connection to the Internet via a gateway in order to upload all collected data to the cloud.

[a] Expected for Massive Machine-Type Communications (mMTC).

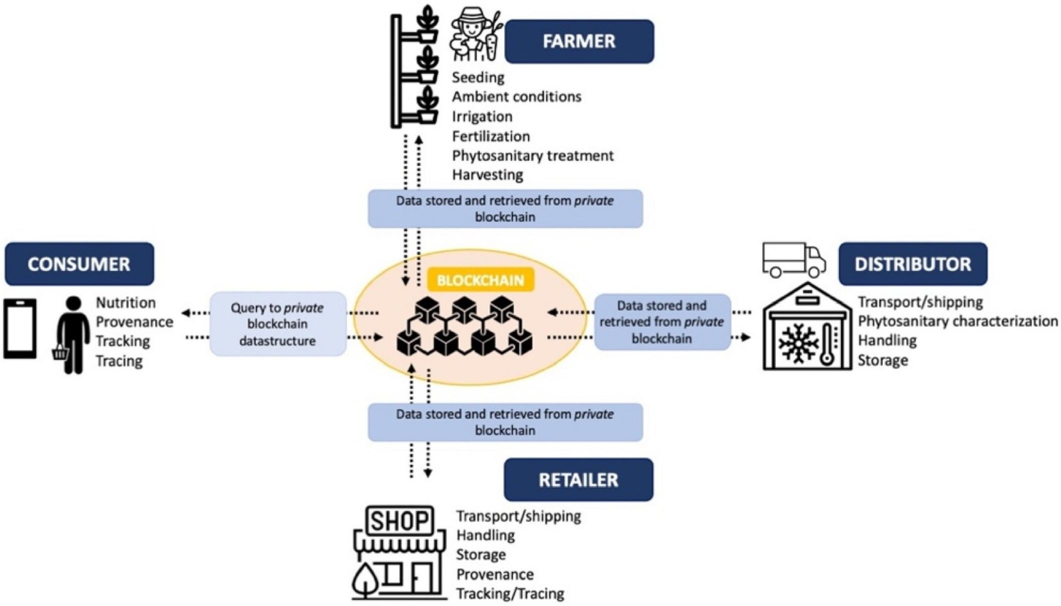


FIGURE 2 Actors and utilities in the proposed blockchain architecture. This diagram depicts the blockchain layer as the core for data integrity and data management within our integrated agricultural system. Interfacing directly with IoT-collected data and the orchestration layer's analytical tools, this blockchain framework ensures that all data is immutable, transparent, and securely shared among farmers, distributors, retailers, and consumers. The layer supports real-time traceability, dynamic pricing models, and logistic efficiencies, among others, which are essential for modernising agricultural practices and enhancing supply chain operations.

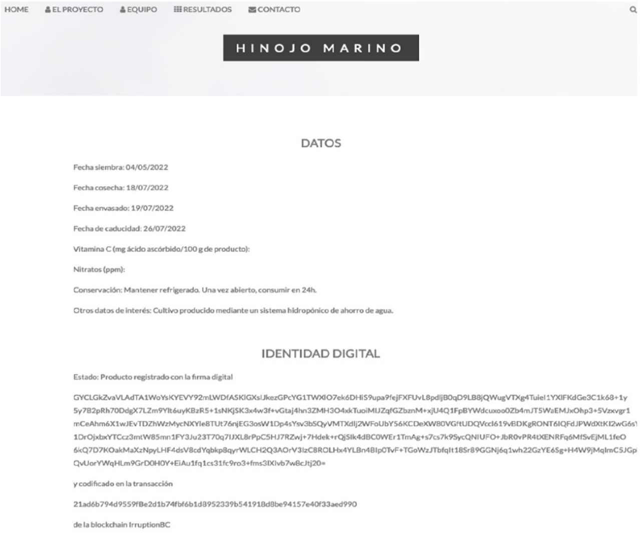
network, defined as Smart Contracts. These contracts define the transaction instructions for managing the data of fresh vegetable products throughout the supply chain. Implemented in *node.js*, the chaincode handles operations such as product creation, updates to the product status as it moves through the supply chain, and querying product history.

The application layer, developed using PHP, *node.js*, HTML, and RESTful APIs, provides a user-friendly interface for interacting with the blockchain network. HTML and PHP are used for the front-end user interface, creating a web-based dashboard where farmers, distributors, and retailers can view and manage the vegetable products' data. The dashboard provides functionalities such as registering new products, updating product status, and viewing product history. *node.js* is used to develop the server-side logic, also known as back-end logic, interfacing with the Hyperledger Fabric network through the Fabric SDK. The SDK offers APIs for interacting with the blockchain, including submitting transactions, deploying chaincode, and querying the ledger. Finally, RESTful APIs serve as the channel between the front-end application and the blockchain network, ensuring secure and efficient communication. The API endpoints are designed to perform specific operations such as creating a new product identity, add new data to an existing product or retrieving product traceability information. The consumer can then obtain the information from the blockchain via the QR code printed in the product tag, loading a web page with the corresponding product data (only the public data stored in the blockchain) as shown in Figure 3.

4.3 | The orchestration layer

Third, the orchestration layer is responsible for boosting innovation. This goal can be achieved with three functions, namely (A) information and data visualisation, (B) information and knowledge generation using apps and smart contracts, and (C) joining and processing data in a decentralised fashion, respectively, represented as A, B, and C in Figure 4. The way these functions can boost innovation from an effectuation perspective is explained as follows:

(a)



HINOJO MARINO

DATOS

Fecha siembra: 04/05/2022

Fecha cosecha: 18/07/2022

Fecha envasado: 19/07/2022

Fecha de caducidad: 26/07/2022

Vitamina C (mg ácido ascórbido/100 g de producto):

Nitratos (ppm):

Conservación: Mantener refrigerado. Una vez abierto, consumir en 24h.

Otros datos de interés: Cultivo producido mediante un sistema hidropónico de ahorro de agua.

IDENTIDAD DIGITAL

Estado: Producto registrado con la firma digital

GYCLGkZvaVLAdTA1WoYsKYEVY92mLWDfASKlGXsIJkezGPcYG1TWXlO7ek6DHiS9upa9fejFXFUvL8pdljB0qD9LB8jQWugVTXg4Tuiel1YXlFKdGe3C1k68+1y
5y7B2pRh70DdgX7LZm9Ylt6uyKBzR5+1sNKjSK3x4w3f+vGtaj4hn3ZMH3O4xkTuoiMIJZqfGZbznM+xjU4Q1FpBYWdcuxoo0Zb4mJT5WaEMJxOhp3+5Vzxvgr1
mCeAhm6X1wJEvTDZhWzMycNXYle8TUt76njEG3osW1Dp4sYsv3bSQyVMTXdlj2WFoUbY56KCDeXW80VGftUDQVccl619vBDKgRONT6IQFdJPWdXtKI2wG6s
1DrOjxbxYTCcz3mtW85mn1FY3Ju23T70q7IJXL8rPpC5HJ7RZwj+7Hdek+rQjSlk4dBC0WEr1TmAg+s7cs7k9SycQNIUFO+JbR0vPR4tXENRFq6MfSvEjML1feO
6kQ7D7KOakMaXzNpyLHF4dsV8cdYqbkp8qyrWLCH2Q3AOrV3IzC8ROLHx4YLBn4BIp0TvF+TGoWzJTbfqIt18Sr89GGNj6q1wh22GzYE6Sg+H4W9jMqImC5JGp
QvUorYWqHLm9GrD0H0Y+EiAu1fq1cs31fc9ro3+fms3IXlvb7w8cJtj20=

y codificado en la transacción

21ad6b794d9559fBe2d1b74fbf6b1d8952339b541918d8be94157e40f33aed990

de la blockchain IrruptionBC

(b)

FIGURE 3 Examples from the preliminary implementation. (a) QR code in packaging. (b) Information shown by the product and data stored in the blockchain.

- Resource utilisation: Effectuation emphasises starting with the resources at hand. When developing agritech solutions, particularly in the context of small-scale farming, such as urban farming, or resource-constrained environments, leveraging existing resources can be crucial. Blockchain-based agritech solutions can be designed to work with the available technology infrastructure and resources, making them more accessible and cost-effective for users. The blockchain implementation requirements for this case where only a server with Linux Ubuntu 22 OS, 4 GB of RAM, and 40 GB for storage, and the following open source software: Apache, PHP, *node*, REST, Hyperledger, and Docker.
- Affordable loss: Effectuation encourages entrepreneurs to consider what they are willing to lose in case of failure. In agritech, this can translate to minimising financial risk for farmers and other stakeholders. By using blockchain to create transparent and efficient supply chains, farmers can experiment with new approaches and technologies without risking their livelihoods, for example, providing offers before cultivation in an 'early-auction' style.
- Crazy quilt: Building partnerships and networks is a key aspect of effectuation. In agritech, blockchain can facilitate collaboration among various stakeholders, including farmers, suppliers, distributors, and consumers. By forming a 'crazy quilt' of partnerships, agritech solutions can tap into the collective expertise and resources of different participants in the agricultural ecosystem.
- Lemonade principle: The flexibility and adaptability of effectuation are well-suited to the uncertainties of agriculture. Agritech solutions can use blockchain to enable quick adjustments in response to changing conditions, such as shifts in market demand, weather patterns, or pest outbreaks. This ability to pivot and find new opportunities can be instrumental in agriculture.
- Pilot in the plane: Effectuation promotes the idea that entrepreneurs can shape their future through their actions. In the context of agritech and blockchain, this means that farmers and agricultural stakeholders can actively participate in the development and implementation of technology solutions that suit their needs. Blockchain can provide a transparent platform for these stakeholders to have a direct influence on the system.
- Transparency and trust: Blockchain's inherent features, such as immutability and transparency, align with the principles of effectuation. These features can help build trust among participants in the agricultural value chain. Farmers and consumers can have confidence in the accuracy and integrity of data recorded on the blockchain, fostering trust in the entire system.
- Customisation: Effectuation encourages entrepreneurs to create solutions that fit their unique context. Blockchain-based agritech solutions can be tailored to specific

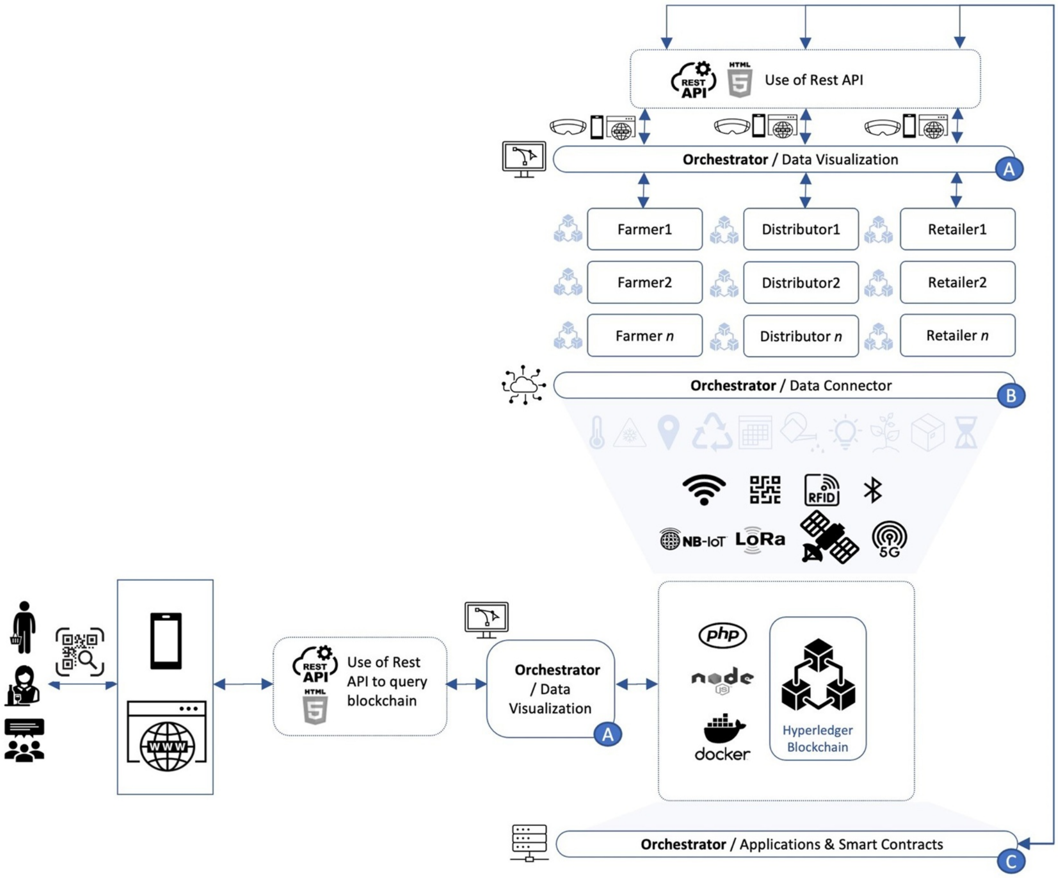


FIGURE 4 Proposed framework for the orquestration layer using the data stored in the blockchain. Function (a) information and data visualisation are about making data accessible and understandable to users through visualisation tools. It allows stakeholders, such as farmers, researchers, and policymakers, to view and interpret the data collected from the fields in real time, facilitating informed decision-making. Function (b) information and knowledge generation processes process the integrated data to generate actionable insights and knowledge using applications and smart contracts. This could involve analysing crop health data to optimise watering schedules or using supply chain data to improve logistics and reduce waste. Function (c) joining and processing data emphasises the decentralised nature of data processing within the system. It involves aggregating data from various sources in a secure and transparent manner, leveraging blockchain technology to ensure integrity and trust in the shared information.

agricultural practices, crops, or regions. This customisation can enhance the relevance and effectiveness of the technology for different user groups.

Incorporating effectuation principles into the development and deployment of agritech solutions based on blockchain and IoT can lead to more adaptive, user-centric, and sustainable solutions. It encourages a mindset that prioritises collaboration, resourcefulness, and risk mitigation, which are particularly valuable in the agricultural sector where uncertainty and variability are common challenges.

4.4 | Communication challenges for the digital twins of field crops

Digital twins create digital replicas corresponding to physical world products and services. Digital twins can also visualise data analytics and enable business organisations to perform simulations based on physical world conditions before making high-cost decisions [39]. Thus, a digital twin is a reflection of the physical state and condition of a single physical object created from IoT-assisted interaction between real life and the virtual world [40]. To achieve a practical digital twin, the reflection needs to be as close as possible to the real-time physical state. IoT can be leveraged to support immersive, wireless, connectivity-rich digital experiences in the metaverse, mapping real-life IoT data in real time to a digital reality in the virtual world.

However, there are some essential requirements for IoT and digital twins to come together. The experience must be immersive, anywhere, anytime, fully operational, interactive, and with authenticity. For the above requirements to be met and for the advantages and vision offered by the digital twins to become a reality, there is one key challenge to be met related to two telecommunication network concepts: Quality of Service (QoS), with requirements in terms of latency, bandwidth, or reliability, and Quality of user Experience (QoE), with requirements such as mobility, response time, scalability, synchronisation, or coverage. It will be necessary to exchange huge amounts of data with ultra-low latency, knowing that the nature of haptic signals and human perception require a maximum latency of 1 ms. To this, we can add that the number of end users can be massive and the services are in real time. It is well known that 4G technology is not capable of providing these requirements. 5G is rapidly developing to provide real-time data exchange to IoT devices, surpassing the speeds of previous systems and providing a high-speed communication architecture suitable for the digital twins by making use of technologies such as mmWave, NOMA and massive MIMO. 6G is expected to extend the features of 5G to fully realise the paradigm using THz communications. However, due to the high carrier frequency used with these technologies, the IoT systems would suffer more severe propagation loss than low-frequency communication technologies such as LTE or LoRa, and it is difficult for these communication signals to penetrate and diffract around obstacles, such as vehicles and buildings in urban areas, with the corresponding impact for indoor and urban farming, which is our use case.

Similarly, it is important to note that IoT data will need to be collected in real time to analyse the behaviour or states of objects in the physical field crop. How to monitor equipment and collect data from all aspects, including initial data, tracking information, operational information, and programme data will be challenging [41], and data mining and analysis need to be performed once the real-time IoT data is collected. The amount of available real-time data may be limited to turn digital twins into useful and accurate tools, which may be due to too small IoT deployments, very preliminary digital transformation processes, transmission problems, or the need for better spatial computing [42] and data fusion techniques [43].

5 | CONCLUSION

The agritech paradigm is joining the information and communication technology sector, characterised by its rapid changes, and agriculture, a long-time, more traditional human activity. New technologies such as IoT and blockchain are showing their advantages to boost efficiency, transparency, and sustainability, among other, when applied to agriculture. In order to bring this idea down to earth, we have proposed an IoT-blockchain-based framework, explained its components, carried out a preliminary implementation using Hyperledger and QR codes as the main technologies, analysed qualitatively the advantages of this system to promote innovation from an effectuation perspective, and finally, identified the communication challenges for an effective deployment of digital twins of urban field crops. As a future work, we will extend the experimental setup. We strongly believe that the integration of the physical field and its digital version at the orchestration layer enables the creation of knowledge to improve productivity across the supply chain, facilitates the development of improved business models and formulation of suitable policies.

AUTHOR CONTRIBUTIONS

Igor Tasic: Conceptualization; investigation; methodology; visualization; writing—original draft. **Maria-Dolores Cano**: Conceptualization; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing—review & editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no competing interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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