IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received July 21, 2020, accepted August 1, 2020, date of publication August 5, 2020, date of current version August 17, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3014522

Blockchain Technology in Current Agricultural Systems: From Techniques to Applications

WEIJUN LIN[1], XINGHONG HUANG[1], HUI FANG[2], VICTORIA WANG[3], YINING HUA[2], JINGJIE WANG[1], HAINING YIN[4], DEWEI YI[5], (Member, IEEE), AND LAIHUNG YAU[6]

[1]Institute of Agricultural Economics and Rural Development, Guangzhou 510640, China
[2]Computer Science Department, Loughborough University, Loughborough LE11 3TU, U.K.
[3]Institute for Criminal Justice Studies, University of Portsmouth, Portsmouth PO1 2UP, U.K.
[4]SAP China, Shanghai 200040, China
[5]Department of Computing Science, University of Aberdeen, Aberdeen AB24 3FX, U.K.
[6]Asia Pacific Applied Nano Technology Research Centre, Hong Kong

Corresponding author: Hui Fang (h.fang@lboro.ac.uk)

This work was supported in part by the Science and Technology Planning Project of Guangdong, China, under Grant 201903010105, and in part by the Philosophy and Social Science 13th Five-Year Planning Project of Guangzhou, China, under Grant 2018GZZK23.

ABSTRACT Increasingly, blockchain technology is attracting significant attentions in various agricultural applications. These applications could satisfy the diverse needs in the ecosystem of agricultural products, e.g., increasing transparency of food safety and IoT based food quality control, provenance traceability, improvement of contract exchanges, and transactions efficiency. As multiple untrusted parties, including small-scale farmers, food processors, logistic companies, distributors and retailers, are involved into the complex farm-to-fork pipeline, it becomes vital to achieve optimal trade-off between efficiency and integrity of the agricultural management systems as required in contexts. In this paper, we provide a survey to study both techniques and applications of blockchain technology used in the agricultural sector. First, the technical elements, including data structure, cryptographic methods, and consensus mechanisms are explained in detail. Secondly, the existing agricultural blockchain applications are categorized and reviewed to demonstrate the use of the blockchain techniques. In addition, the popular platforms and smart contract are provided to show how practitioners use them to develop these agricultural applications. Thirdly, we identify the key challenges in many prospective agricultural systems, and discuss the efforts and potential solutions to tackle these problems. Further, we conduct an improved food supply chain in the post COVID-19 pandemic economy as an illustration to demonstrate an effective use of blockchain technology.

INDEX TERMS Blockchain technology, agricultural applications, food supply chains management, data integrity, traceability.

I. INTRODUCTION

Current agricultural development and reform are calling for new techniques and innovations to create a more transparent and accountable environment in the agriculture sector. One of the emerging tools is blockchain technology. Unlike conventional centralized and monopolistic agricultural management systems, blockchain provides a decentralized data structure to store and retrieve data that are shared with multiple untrusted parties. In this way, it could potentially resolve a number of serious problems in current systems caused by the following reasons: (i) hackers can easily attack the centralized system to tamper data integrity; (ii) insider manipulation of the centralized database could compromise data integrity; (iii) a supply chain management system is over-reliant on the centralized database (single point failure problem); and (iv) high costs when involving a third party to verify and monitor transactions. To solve these issues, distributed database enhanced by advanced cryptography is proposed in the past few decades. Among these, blockchain is one of the most predominant emerging methods to solve trust related issues generated by the invention of Bitcoin in 2008 [1].

In blockchain technology, many advanced computational and cryptographic techniques are integrated into distributed data structure to achieve a digital trust system in an untrusted environment [2]. In particular, hash function, as an algorithmic way to generate unique IDs, is used as the key element for data authentication. Hash values can be embedded into

The associate editor coordinating the review of this manuscript and approving it for publication was Yassine Maleh.

a format of stored chain to verify whether the stored data are tampered to ensure data integrity. Digital signature is used to verify real identities of data senders and receivers in stored transactions. In addition, consensus mechanism is designed to involve all computer nodes thus minimizing potential risks of data being manipulated by minority attackers.

Blockchain applications in agriculture enhance diverse aspects in agricultural systems, especially supply chain [3] and Internet of things (IoTs) based systems [4]. These applications include food safety [5], food security [6], food quality monitoring and control [7], traceability for waste reduction [8], reliable operational data analysis [9] and efficient contract exchanges and transactions to reduce economic costs [10], thus supporting small-scale farmers [11]. These applications can be developed by using existing blockchain platforms to facilitate easy and quick developments. Based on different deployment scenarios of these applications, different computational and cryptographic techniques can be plugged to provide flexibility to meet desperate user requirements.

In this paper, we present a comprehensive survey on the blockchain based agricultural applications and current innovations to promote blockchain techniques. We first explain basic concepts of blockchain technology, illustrate the current data storage ecosystem and analyze existing popular platforms by which the developed applications are implemented. Then we provide a comprehensive survey on diverse blockchain applications in agriculture related projects. After the survey, we further discuss the prospective of the emerging technology and how current challenges could be solved in deployment of the systems. Further, an illustration is presented to demonstrate how blockchain can be improved to build a more reliable and efficient food supply chain in future.

This research is based on existing literature. We have used a comprehensive literature search strategy. We first gather all relevant survey papers by complying with the systematic procedure via searching the relevant subjects in Google Scholar and many electronic databases, including Open Athens, IEEE Xplore and Science Direct. The search terms used to collect the relevant works are: blockchain for agricultural applications, blockchain for supply chain management, blockchain for IoT, data integrity, traceability, provenance, and IPFS with blockchain. All these terms are used in multiple search combinations to ensure the completion of data gathering. The comprehensive literature review is crucial for us to answer the following three main research questions: (1) What are the current standard blockchain applications in agriculture related projects? (2) What are the main challenges that these blockchain applications face in their deployments? And, how could these challenges be met? (3) How blockchain can be improved to build a more reliable and efficient food supply chain in the future?

The contributions of our work can be highlighted as: (i) we make an insight investigation of the existing applications of blockchain in agriculture and highlight potential uses of the technology, (ii) we suggest suitable blockchain schemes in the agricultural sector by an illustration of the technical details of the key components in blockchain technology, (iii) we further identify the key challenges in many novel agricultural applications and discuss alternative solutions, and (iv) we present a post COVID-19 pandemic blockchain based supply chain system to improve the resource allocation when dealing with unexpected event emergency. Although there are many new blockchain survey papers published in recent years [12]–[21], our work provides a comprehensive study in the agricultural context. In the work, both technical details and applicative aspects are covered so that our insights could be used to suggest suitable techniques and platforms for individual applications in their own agricultural scenarios.

The structure of this paper is organized as follows: In Section II, computational and cryptography algorithms used in blockchain technology are explained in details. In Section III, the latest blockchain applications are categorized and critically reviewed. Following the review, the challenges and prospective of combining blockchain with other emerging technologies are discussed in Section IV. Further, we present an illustration how blockchain can be deployed in a real-world scenario in Section V. Finally, the conclusion is drawn and future work is suggested in Section VI.

II. BLOCKCHAIN TECHNIQUES

As a formal definition, blockchain is a distributed ledger to share transactions or sensitive data across untrusted multiple stockholders in a decentralized network [22]. A basic blockchain structure is illustrated in Fig. 1. The data are recorded in a sequential chain of hash-linked blocks that facilitate the data distribution in a more manageable manner comparing to other traditional data storage formats. The blocks are verified and uploaded into the chain-like system by selected nodes via an agreed consensus protocol. This consensus mechanism allows all the parties to engage in the monitoring process when adding data/information flow on-chain. In addition, the duplicates of these data are stored in all involving nodes to ensure their tamperlessness. In this section, a high-level review of blockchain ecosystem and technical details of the implementation are provided before the investigation of current blockchain applications in the agricultural sector.

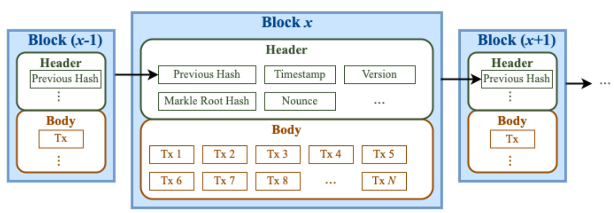

FIGURE 1. The data structure of a blockchain.

A. DATA STORAGE ECOSYSTEM

Data storage and retrieval solutions are playing a centric role in agricultural systems. The ecosystem of data storage is

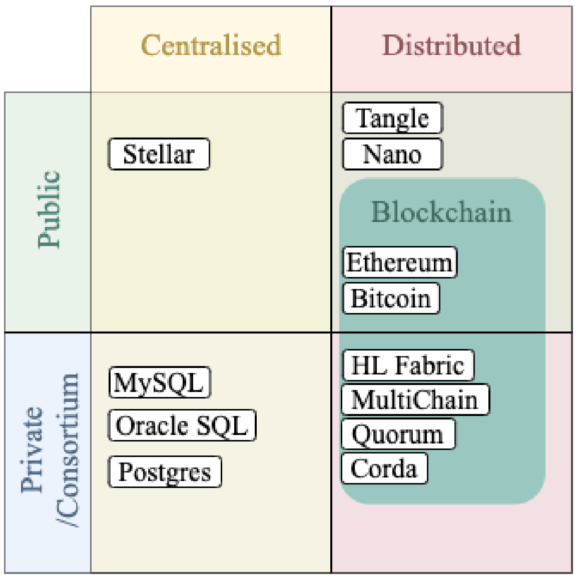

FIGURE 2. The data storage ecosystem. Blockchain is playing an important role in the ecosystem.

illustrated in Fig. 2. Typical systems are still using conventional databases, such as MySQL, Oracle SQL and Postgres, to store and use data in a centralized way. They assume that data are synchronized well and shared among trusted parties. However, it is hard to hold the assumption in most real-world systems. Information asymmetric problem emphasized in [23] is a major issue to hinder the efficient allocation of resources in typical agricultural supply chains. As a variety of untrusted parties with different geographic locations are involved to generate data in a supply chain, it requires a more tamper-free system to protect the sharing of data across parties. The robust and decentralized features of blockchain offer one of the most suitable solutions by improving data transparency as well as data integrity without paying a third party to verify the process.

Apart from the centralized solutions, blockchain systems dominate the distributed database solutions. Three types of blockchain systems are defined based on the accessibility and security level of applications: (1) public blockchain; (2) consortium blockchain; and (3) private blockchain. Public blockchain system can be joined by any nodes across the world with internet connection. The public blockchain is fully transparent so that data are difficult to be tampered by any internal or external attackers. However, the high decentralization trait of these systems generates large redundancy as well as less efficiency when considering the burden of sharing large amount of data. Therefore, the public blockchain is more suitable to applications with relatively small number of transactions (or data) to store into the blockchain system. Typical public blockchains include bitcoin [1] and Ethereum [24]. The private blockchain is deployed by a single party. It shares many similar characteristics to those centralized solutions but with a blockchain architecture. Although it is argued that private blockchain systems can be replaced by conventional solutions, it offers advantages over the centralized data storage when they are attacked by insiders. The consortium blockchain refers to a solution to keep data privacy and fast on-chain speed but involving more than one party for data storage. It is the most popular type in agricultural supply chain applications since having a balance performance, it fits most user requirements in this sector. Many blockchain platforms, such as Hyperledger Fabric [25], MultiChain [26], Quorum [27] and Corda [28], can be used to deploy either consortium or private blockchain systems.

B. BLOCKCHAIN TECHNICAL COMPONENTS

Several essential techniques, including hash, asymmetric cryptography, digital signature, Merkle tree and consensus are utilized in the blockchain design to achieve a secure ledger with decentralized management. Specifically, each block has a block header and a block body. In block header, several elements are included, such as previous block hash value, nonce, Merkle tree root hash, and other information, e.g., block version and Timestamp. Block body holds the actual data that are either transaction records or the protected data.

1) HASH FUNCTION

Hash function is a key technique in blockchain, which is used for multiple purposes, including address generation, digital signature and consensus. Through hash function, arbitrary size data can be easily mapped to fixed-size values. While inversely, it is difficult to restore the original data from its hash value. For example, with a given large data x, its corresponding hash value can be obtained by irreversible hash function, $Hash(x)$. If x is modified to x' in an unintended manner, the hash result $Hash(x')$ is completely different from $Hash(x)$. Two most common hash functions used in blockchain include message digest 5 (MD5) and SHA256 based on the complexity of data [29].

During network transmission, data integrity can be verified by cryptographical hash technique. For example, assume Alice sends data x to Bob. Along with data x, the encrypted hash value $Encrypt(Hash(x))$, is also enclosed. After Bob receives the data, he can verify data integrity by calculating the hash value from received data x', $Hash(x')$, and comparing it with the expected hash results decrypted from the received $Encrypt(Hash(x))$. If $Hash(x') = Hash(x)$, it means data is transmitted properly, $x' = x$. Otherwise, if $Hash(x') \neq Hash(x)$, it means data integrity has been broken, so Bob may ask Alice to transmit the data again.

2) ASYMMETRIC CRYPTOGRAPHY

To implement verifiable transaction in distributed system, asymmetric cryptography technique [30] is used along with hash function to enforce digital signature technique. In asymmetric cryptography, each user has a pair of keys, i.e. private key k and public key K. The private key is kept confidentially and known only by the owner, while the public key could be known by the others. The public key can be calculated from the private key, but with given public key, private key cannot be obtained in reverse. The public key K and the private key k can encrypt and decrypt data in pairs. For example, as shown in Eqn. 1, data x encrypted by public key K can be decrypted by corresponding private key k. On the other hand, data x encrypted by private key k can also be decrypted by corresponding public key K.

$$Decrypt_k(Encrypt_K(x)) = Decrypt_K(Encrypt_k(x)) = x \quad (1)$$

Targeting different security requirements, asymmetric cryptography can be flexibily applied. Again, assume Alice is sending data x to Bob, and both of them have a pair of asymmetric key. Note, Alice and Bob know each other's public key whereas their private keys are only known by themselves, individually. To ensure confidentiality, Alice can encrypt data x through Bob's public key, $Encrypt_{K_B}(x)$. Hence, only Bob can decrypt the data by using his private key. On the other hand, to ensure authentication and non-repudiation, Alice should send data x encrypted by her own private key, $Encrypt_{k_A}(x)$. In this case, after receiving the transmitted data, Bob can attempt to decrypt it by Alice's public key. If successful, these data are indeed sent by Alice and she cannot deny it.

3) DIGITAL SIGNATURE

For each blockchain transaction, digital signature [31] is required to avoid issued transaction being modified or denied. Technically, digital signature is an integrated technique utilising both hash function and asymmetric cryptography. Like the signature for paper documents, a valid digital signature ensures that an unaltered data is sent by a known sender, which cannot be repudiated. For this purpose, the file is firstly hashed to a fixed length and then encrypted by sender's private key, and the result refers to the digital signature of this sender. Since only nominated sender has his own private key, the asymmetric cryptography technique ensures authentication and non-repudiation of this signature. Meanwhile, because anyone can obtain the sender's public key, the integrity of signature can be verified by anyone through calculating the hash value from the data and comparing it with the hash value decrypted from the signature. Moreover, if confidentiality is also required, the data can also be encrypted by the public key of nominated receiver.

4) MERKLE TREE

Once the number of transactions becomes larger, doing verification by downloading all the antiquated transactions in blockchain consumes a large amount of storage resource. To address this issue, Merkle Tree technique is used to reduce the storage data without breaking the block's hash [32]. Merkle Tree is a binary tree consisting of leaf hash nodes, intermediate hash nodes and a root hash node. In each block, leaf hash nodes are the hash values of individual transactions. For example, assume there is a block with transaction data T_A, T_B, T_C and T_D. Here comes a Markle Tree with 4 leaves, i.e. $Hash(T_A)$, $Hash(T_B)$, $Hash(T_C)$ and $Hash(T_D)$. As the parents of these leaves, two intermediate hash nodes, $Hash_{AB}$ and $Hash_{CD}$, are calculated as follows.

$$Hash_{AB} = Hash(Hash(T_A) + Hash(T_B)) \quad (2)$$

$$Hash_{CD} = Hash(Hash(T_C) + Hash(T_D)) \quad (3)$$

Finally, the value of root hash, which is included in the block header, is calculated by hashing the value of intermediate nodes, as shown in Equ. 4.

$$Hash_{ABCD} = Hash(Hash_{AB} + Hash_{CD}) \quad (4)$$

To this end, by stubbing off branches of the tree, old blocks can then be compacted to reduce the size of the blockchain.

5) DISTRIBUTED CONSENSUS SCHEMES

Byzantine general problem [33] has been raised as a trust issue in distributed systems. It refers to the data tamper caused by some dishonest nodes under the blockchain context [34]. The consensus mechanism is proposed to solve the problem and protect the data from minority attacks by allocating the responsibility of updating data blocks to random candidates selected from all the nodes. The popular consensus mechanisms include Proof of Work (PoW), Proof of Stake (PoS), Delegated Proof of Stake (DPOS), Practical Byzantine Fault Tolerance (PBFT), and Proof of Elapse Time (PoET).

PoW is the first proposed scheme in the bitcoin to achieve consensus in peer to peer management [1]. The nodes across the network compete with each other to solve a cryptographic puzzle to add the next block into the blockchain with a small amount of incentives. This is called "mining" in blockchain based cryptocurrency. Although the scheme is remarkable to protect the blockchain system from malicious attacks, it is a time-consuming and energy consumption process. Therefore, the on-chain speed (transactions per second) is low in the systems by using this scheme.

PoS is a mechanism to use validators instead of miners to update the blocks [35]. The nodes must prove their stakes by depositing certain amount of coins in the system. The key advantage of the PoS over PoW is the significant reduction of the computational power. However, the main issue is that the nodes who have large proportion of stakes are more likely to become the validators of the blocks. Delegate Proof of Stake (DPoS) [36] is an improved version of PoS by restricting the number of validators to further improve the scalability of the blockchain. Block producers are voted by all the users who have a number of votes calculated based on their stakes on the network. A block is generated if two third of producers reach an agreement.

Practical Byzantine Fault Tolerance (PBFT) algorithm was initially proposed to target on the Byzantine general problem [37]. It highlights that the PBFT requires 3f+1 nodes to make a correct decision if f nodes are faulty/dishonest nodes in the network. The algorithm has been adopted into a blockchain system as one alternative consensus scheme [34]. In the scheme, a block proposer is first selected based on a robin-round manner. The proposer will then broadcast and collect 3f+1 nodes in the network. If two third of the validators agree on a block proposal, the block is valid to commit into the blockchain.

Proof of Elapsed Time (PoET) is a more efficient mechanism compared to other consensus schemes [38]. It was developed by Intel on top of the SGX technology. After signing attestation, each node participates in a randomized lottery selection by receiving an object timer from the trusted code. The node who wakes first will lead the next block creation. However, the SGX is made by Intel which is a third-party company. This has a potential to compromize the principle of blockchain to remove the intermediaries.

Overall, consensus scheme design is still an open challenge in blockchain research [39]. The selection of the scheme relies on the application context to balance the block on-chain speed as well as the robustness to against various types of attacks.

C. BLOCKCHAIN GENERATION PROCESS

Blockchain data on-chain process has several stages to secure data integrity. An example of a transaction record on-chain process is illustrated as follows:

Stage I: Before each transaction, payee address is firstly generated, and the payer makes payment to that address. After the payer finishes the payment, the transaction is digitally signed by both the transactions parties and broadcasted to all the participants (i.e. peers) in the network. From the participant side, after receiving a new transaction, the transaction is firstly verified, and if valid, collected into a block.

Stage II: Every participant packs the collected transaction records during a period into a block, and make an effort to upload his block to the blockchain. Regarding which participant can stand out from the peers, various distributed consensus schemes are introduced in previous section.

Stage III: When the new uploaded block is connected with the existing chain, it is broadcasted to all the other participants in the network. After receiving the block, other participants can verify all transactions in the block to ensure data integrity. Since each block in the chain requires the hash value of the previous hash, the participants can express their acceptance of specific chain by using its hash to create the next block.

With repeating these stages, all the data can be stored in the decentralized database sequentially. It provides a transparent environment for all the stakeholders so that a trusted system is built across the network.

III. BLOCKCHAIN APPLICATIONS IN AGRICULTURAL SECTOR

During recent years, blockchain has attracted significant increasing attentions in agricultural sector. This trend is driven by the major concerns in several important aspects, i.e. food contamination and fraud issues [40], data security and safety in smart farming [41] and IoT based precision agriculture [3], trust and efficiency issues in financial transactions in the agricultural supply chain [42] and data transparency and integrity of agriculture related information management systems [43]. The regulation and governance seek for more innovations on adopting blockchain techniques to achieve better data transparency and accountability with flexible, costly and sustainable solutions. As illustrated in Figure 3, all the stakeholders involved in agricultural production and transaction can secure their data integrity in blockchain based systems. Thus, users have high confidence when using the products or the services offered by them.

A. APPLICATION CATEGORIES

In this subsection, a comprehensive investigation has been made to identify how the blockchain technology are deployed to achieve efficiency and integrity of agricultural applications. Based on these targeted issues, we categorize uses of blockchain into four groups: (i) provenance traceability and food authentication; (ii) smart farming data management; (iii) trade finance in the supply chain management; and (iv) other information management systems.

1) PROVENANCE TRACEABILITY AND FOOD AUTHENTICATION

The most popular use of blockchain technology in agriculture is the traceability and provenance function in product supply chain management. It is the most efficient way to enhance food safety, and reduce fraud and food scandals since all relevant data related to the product origin and its movements can be stored with minimal tampering risk [44]. When each product item is produced, a corresponding digital token is attached to the item in order to ensure that it is tracked at a real-time manner. The developed applications include tracing Pork and Mango sold in Walmart supermarket [45], egg distribution from farm to the fork at midwestern U.S. [46], Brazilian grain export [47], the certificate verification of table grape shipped from Africa [48], the use of RFID tags to trace cold chain food [49], and the use of IoT sensor to trace products in supply chain [50].

Walmart is one of the pioneers to deploy blockchain on food traceability [45]. It worked closely with IBM to deploy two pilot studies by using Hyperledger Fabric. These two studies include the traceability systems for pork in Chinese market and mangoes in the American market. E-certificates including agricultural treatments, ID numbers, manufacturers, security issues, permissions and safety related records are all stored in the log files. With blockchain technology, procurement managers can trace all the information online in time, so that they can easily pinpoint the individual tainted products without recalling all the products. The systems can not only make the safety traceability much more quickly but also cut the recall cost by allowing to trace the items instead of batches [45].

Data and transactions collection procedure in the blockchain traceability systems are designed based on requirements of the applications. In [51], different event types defined in the Electronic Product Code Information Services (EPCIS) specification [52], including ObjectEvent, AggregationEvent, QuantityEvent and TransactionEvent, are

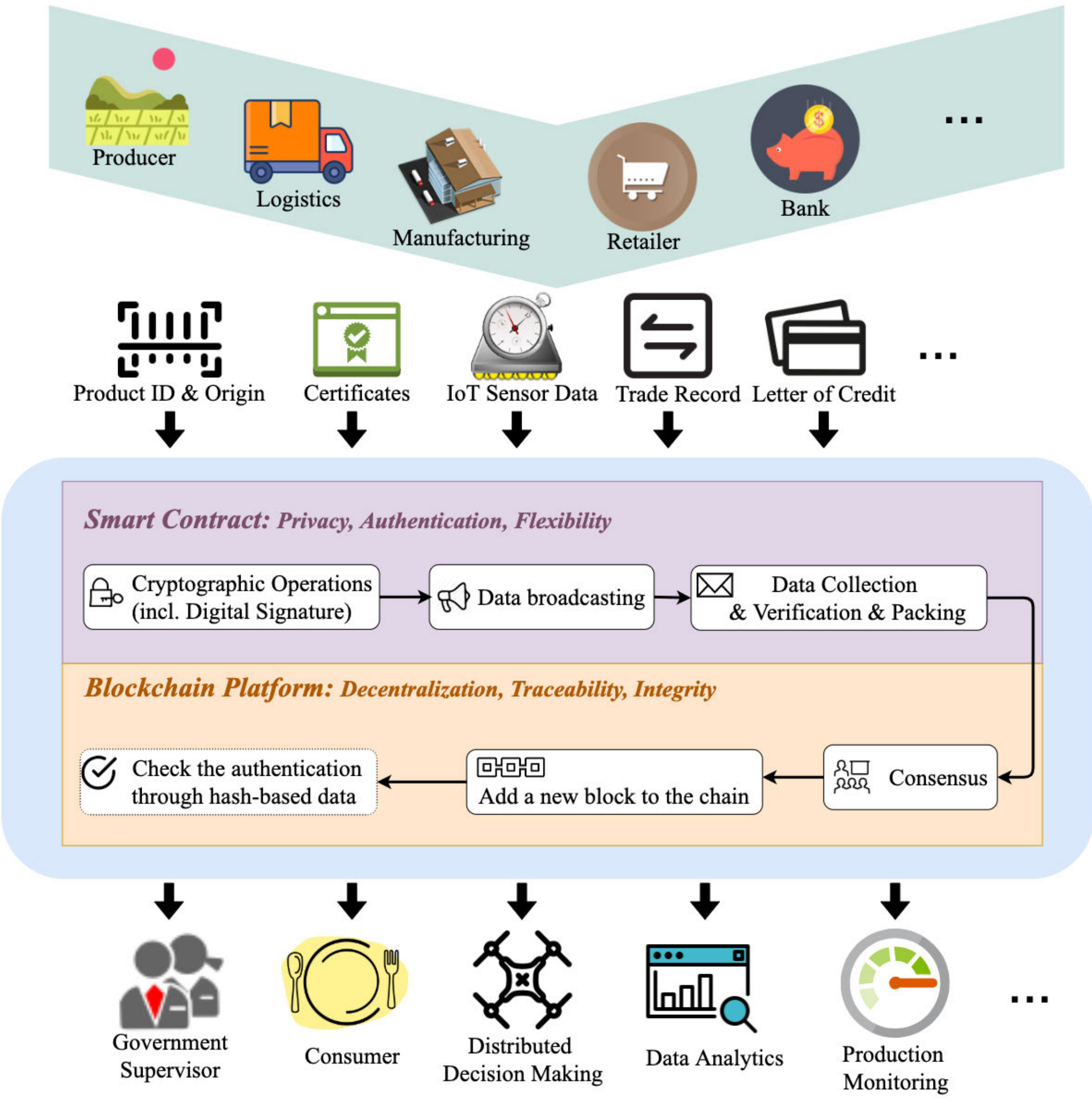

FIGURE 3. Agricultural stakeholders, including producers, logistic companies, manufacturers, retailers and financial institutions, can be involved to create blockchain applications to build up trust of data users, e.g., goverment supervisors, consumers, and other AI and machine learning based systems.

uploaded into the blockchain to ensure the better information traceability as the items and their main transaction events have unique codes. In [48] and [53], certification documents of the products are embedded into the transactions to satisfy the compliance with health and safety regulations. In other traceability systems, such as [49] and [50], using IoT sensors or RFID tags to automate the data collection could further reduce the manual mistakes for data integrity and improve the efficiency of data on-chain process.

2) SMART FARMING DATA MANAGEMENT

In addition to the previous mentioned traceability systems, IoT techniques have also been widely used in smart farming for better productivity control and management [54]. In these IoT sensor-based systems, management and control decisions are made based on data collected from sensor networks. In [55], robotic swarm control is proposed as a key concept in future smart farming and precision agriculture. Simply put, UAVs and land robots could make either distributed or collaborative decisions based on data collected from robotic swarms and communications between them. Thus, data privacy and integrity are the most important component in such systems.

There exists an increasing trend of migrating IoT network data from centralized database to blockchain systems for many applications [56], [57]. Many agricultural projects have benefited from the convergence of IoT and blockchain techniques. For example, IoT based irrigation systems are proposed in [58] and [59] and blockchain is deployed to keep sensing data privacy and integrity. In [60], a private blockchain is adopted to secure monitoring and control data in a fish farm so that all the control decisions are accountable. In [61], Kawakura *et al.* uses Corda to build an IoT data recording system to store data that farmers operate hoes with small data transaction time-delay. With the analysis on these data, farming operations can be optimized to increase productivity. In these applications, farmers can build up their trust on the automated controllers as all decisions are accountable.

3) EFFICIENCY IMPROVEMENT OF THE TRADE FINANCE IN THE SUPPLY CHAIN

blockchain was originally proposed to improve the financial efficiency, and reduce transaction cost by removing intermediaries and audit cost via improved accountability in trading business process [72]. This feature is powerful to support small scale farmers who are suffering from high cost of trade transactions and accidental losses caused by environmental disasters or other uncertainties [73]. Therefore, the straightforward use cases of blockchain in agriculture is to explore its financial functions to make these agricultural producers profitable.

Many agriculture related companies are developing blockchain systems to support trading parties in supply chain management. In [23], an integrated food trading systems with consortium blockchain, called FTSCON, was built to facilitate costly and easy trading of agricultural products in Shandong province, China. Based on the trial between 2014 and 2017, it was found that the total profit of different enterprises in the region increased significantly. In [64], a detailed solution of implementing a trading system in soybean supply chain was presented. It emphasized that this system could provide proof of delivery, automated payments and dispute handling. In [66], a case study was made by CBH group in Australia to secure the seven days payment terms via a Quorum based blockchain system.

The blockchain technology is also under development to support agricultural finance by many financial institutions and commercial banks. In [67], several case studies of blockchain systems which were jointly developed by banks and IT companies to illustrate that the blockchain systems provided the letter of credit from the banks efficiently to speed up the trading process with much shorter period. In [65], State Farm and USAA jointly developed a system to facilitate the automatic insurance claims from farmers to reduce the fraud risk as well as improve the claim efficiency. All these innovations have motivated farmers to produce more products by increasing their profit margins.

4) OTHER AGRICULTURE RELATED DATA MANAGEMENT SYSTEMS

blockchain technology is considered as the next generation information infrastructure promoted by many countries [74]. It has made significiant impacts on both industrial and research projects. In food manufacture industry, a food quality monitoring system is built by combining smart contract and evaluation models to increase reliability of peach juice production process [68]. On the agricultural research side, it is also calling for more transparent ways to increase confidence on research results when multiple collaborators are involved in a project. For example, food science research society proposes to use blockchain to store and share collected research data [70].

Blockchain based systems have also been deployed in many other agriculture related information management systems as the backbone infrastructure. For example, in [69], a decentralized ledger-based contract management system is built to provide legal protection of the temporary agricultural workers in Italy. In addition, the payment of the salary can be settled via the cryptocurrency in this integrated system. In [71], Plastic Bank uses a blockchain based token to encourage the plastic waste collection and recycle to provide an innovative solution for agricultural land cleaning.

B. APPLICATION PLATFORM

As many cryptographic techniques are used in blockchain technology, it is a time-consuming task to build a blockchain system from scratch for practitioners and researchers. As a result, many open source and commercial platforms are provided to simplify and speed up the decentralized application (DApp) development in agriculture related projects. The predominant platforms used in these blockchain practices are discussed as follows.

- **Ethereum** was initiated in 2014 and it is the most active blockchain platform in the world for blockchain practitioners and researchers [24]. It is a permissionless blockchain that is friendly to public blockchain based APP development. The access control can only be added via the smart contract that is limited. Many proof-of-concept agricultural traceability systems, such as [49], [51], [62], [63], finance trading systems, such as [23], [64], and some information management systems, including [68], [69], are deployed on top of the platform. However, there are some disadvantages of using the Ethereum platform for development: as shown in Table 2, the platform uses PoW as its consensus scheme, thus the on-chain speed is relatively low, i.e. $\sim$20 tps [75]. Another constraint for DApp development on the platform is the cost when committing data and transactions on the blockchain via ETH gas, a unit to measure the computational use [76]. When building a system with intensive on-chain data, it is not economic to use this platform.
- **Hyperledger** is endorsed by Linux foundation to provide several distributed ledger frameworks, e.g., Fabric, Sawtooth, Indy, and Burrow [77], for the enterprise level blockchain development. In these frameworks, **Hyperledger Fabric** [25] and **Hyperledger Sawtooth** [78] are the two most popular platforms for the development of the agricultural related projects. The examples include [45], [47], [53] by using Fabric and [46], [50] by using Sawtooth. The default consensus scheme in the Fabric is PBFT while in the Sawtooth, PoET is set as the

TABLE 1. A comprehensive list of blockchain based agricultural systems and their implementation platforms.

Blockchain Applications	Description	Category	Platform
Walmart Traceability Pilot [45]	Trace the origin and production of Pork and Mango in Walmart	Traceability	Hyperledger Fabric
Use case of egg distribution [46]	Trace egg distribution from farm to consumer at midwestern U.S.	Traceability	Hyperledger Sawtooth
Brazilian Grain Exporter [47]	Help the producer in Brazil to track grains to trade with global exporters	Traceability	Hyperledger Fabric
Agrifood Use Case [48]	Verify the certificates of table grape shipped from Africa and sold in Europe	Traceability	Hyperledger Fabric
E-Commerce food chain [53]	Design a tracking and certificate system for e-commerce food supply chain	Traceability	Hyperledger Fabric
Food safety traceability [51]	Combine blockchain with EPCIS standard for reliable traceability system	Traceability	Ethereum
Product transaction traceability [62]	Implement product traceability system with evaluations of deployment costs and security analysis	Traceability	Ethereum
OriginChain [63]	Blockchain to trace the origin of products	Traceability	Ethereum
RFID traceability [49]	Use RFID tags to trace cold chain food in the entire supply chain	Traceability	Ethereum
AgriBlockIoT [50]	Traceability of all the IoT sensor data in an entire supply chain	Traceability	Hyperledger Sawtooth & Ethereum
Water control system [59]	Smart agriculture scenario for irrigation system of plants to reduce water waste.	Smart Farming	Ethereum
Smart watering system [58]	Integrate a fuzzy logic decision system with blockchain storage for data privacy and reliability.	Smart Farming	Customized (Java)
Fish farm monitoring [60]	Secure all the monitoring and control data in a fish farm.	Smart Farming	Hyperledger Fabric
Robotic Swarm [55]	Swarms of robots to deliver precision farming with distributed decision making.	Smart Farming	Multichain
IoT-Information [61]	Information sharing system for accumulated timeline of hoe acceleration data	Smart Farming	Corda
Business transactions on soybean [64]	Track and complete business transactions in soybean supply chain	Finance	Ethereum
FTSCON [23]	Food trade system with consortium blockchain (300 agri-food enterprises in Shandong to trade on the system)	Finance	Ethereum
State Farm Insurance [65]	State Farm and USAA to use blockchain for farming insurance auto-claim	Finance	Quorum
AgriDigital [66]	CBH group from Australia to secure seven days payment terms and trace organic oats	Finance &Traceability	Quorum
Letter of Credit (L/C) [67]	Case studies, including Barclays, Mizuho and Marubeni, Maerssk, HSBC and BBVA deploy blockchain enabled L/C.	Finance	Hyperledger Fabric, Ethereum, Corda
Fruit juice production monitoring [68]	Fruit juice production monitoring by integrating evaluation models into smart contracts	Others	Ethereum
D-ES system [69]	Temporary agricultural employment contracts management and payments for the daily work	Others	Ethereum
Food science research Management [70]	Support the management of functional food research data	Others	Hyperledger Fabric
Plastic Bank [71]	Use blockchain based token to encourage land cleaning by plastic gathering for environment protection.	Others	N/A.

default consensus scheme. In addition, these are flexible to adopt any other schemes to further improve the on-chain speed efficiently. Regarding the performance, both platforms have higher on-chain transaction throughput comparing to the Ethereum. In [79], it uses Fabric to achieve 20,000 tps with delegate design of

TABLE 2. Table to summarize the main features and attributes of the popular blockchain platforms to deploy agricultural applications.

	Ethereum	Hyperledger Fabric	Hyperledger Sawtooth	Quorum
Transaction throughput	Low	High	High	Medium
Consensus	PoW	PBFT & Plugable	PBFT, PoET & Plugable	Raft or Istanbul BFT
Smart contract languages	Solidity	Java, Javascript, GOLANG, Python		Solidity
State databases	LevelDB	LevelDB or CouchDB	LMDB	LevelDB
Access control	limited control via Smart Contract	Access control lists (ACL)		Centralized enforcement

the architecture. The difference between these two platforms is that Fabric supports permissioned blockchain but Sawtooth support both the permissioned and permissionless blockchain development. Thus, the use of Hyperledger frameworks is increasing significantly in agricultural applications.

- **Quorum** was created by JP Morgan to target on enterprise level blockchain systems [27]. It provides an Ethereum based platform to support applications of finance, supply chain, and retails with extra protection on the privacy of transactions and contracts. The transaction data are encrypted to preserve data privacy. In addition, it offers centralized enforcement on the access control so that it is more suitable for private/consortium blockchain systems. Although the platform is built on top of Ethereum, it uses either Raft [80] or Istanbul BFT [81], as its consensus scheme. Therefore, the average transaction speed can reach ∼500 to ∼700 tps in average [27]. Examples of agricultural systems developed by using the platform include AgriDigital [66] and insurance claim [65].

Although there are many other platforms for blockchain based system development, such as Multichain [26], R3 Corda [28] and BigChainDB [82], these four platforms have been widely chosen for the deployment of agricultural systems. The main features and attributes of these platforms, including transaction throughput, consensus, supported smart contract languages, state database and access control, are summarized in Table 2. In addition, a more comprehensive list of agricultural projects by using these platforms are presented in Table 1.

C. SMART CONTRACT

1) SMART CONTRACT AND ITS IMPLEMENTATION

Smart contract refers to a computerized program which is consisted of states, values, addresses and logical functions that are required at the business model layer in a system [83]. The idea was initialized by Nick Szabo in [84] to automatically execute contracts to improve efficiency of business models involved. As illustrated in Fig. 4, smart contract plays a key role in a blockchain system implementation. In specific, once it takes the transaction requests as input to trigger the business logic, it uses defined policy to get the endorsement from peers in the blockchain network. After receiving all the endorsements, it calls the ordering services to verify the endorsement and add the verified transactions into blocks of the blockchain. The records stored in the blockchain is immutable so that no one could tamper the on-chain data. In addition, DApps can query the states of accounts or transactions via the smart contract.

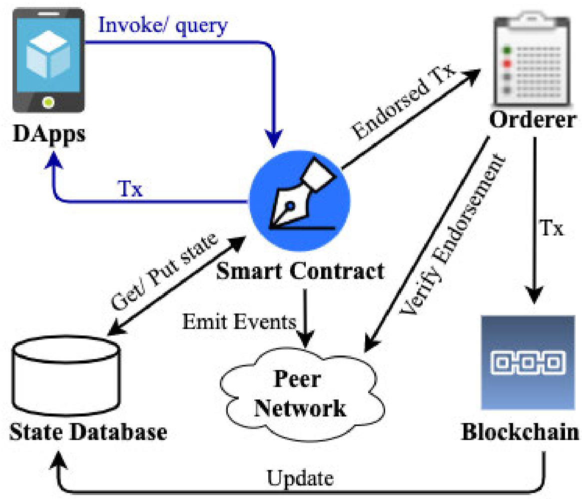

FIGURE 4. Smart contract plays an important role in transaction endorsement and verification.

To support the fast blockchain application development, most blockchain platforms support the programming of smart contracts to fulfil the different business logics behind these applications. Ethereum platform and its extension platform Quorum provides Turing complete smart contracts: they compile either Solidity and Serpent code into Ethereum virtual machine (EVM) bytecodes and the EVM takes responsibility to track state changes to ensure Turing completion. As the most active platforms in Hyperledger family, Hyperledger Fabric and Sawtooth uses Golong, Java, Python and Javascript as the main programming languages for smart contract development.

2) CHALLENGES OF SMART CONTRACTS

The challenges of smart contract is the key focus when blockchain technology is deployed in agricultural systems [93]. In [94], these challenges are summarized based on the smart contract life cycle, which includes creation, deployment, execution and completion stages.

In the creation stage, function and readability issues are faced by the developers and practitioners. Developing human readable code and achieving expected functionality are crucial for accountability of smart contracts. Further, good smart contract design could solve the problem of under-optimized code, which could lead to extra costs in transactions, or underpriced operations resulting denial of service (DoS) attacks. In the deployment stage, contract correctness and control flow are two major factors that ensure high quality of smart contract. Many methods, such as bytecode analysis [95], formal verification [96], and graph-based analysis [97], are proposed to check correctness and control flow of smart contracts for deployment. In the execution stage, execution efficiency of smart contract must be garanteed. In [98] and [99], concurrent execution of smart contracts by proposing Software Transactional Memory based approaches can significantly improve the execution efficiency.

In the final completion stage, security of smart contract is the most crucial factor. As discovered in [95], 8,833 out of 19,366 smart contracts deployed on Ethereum have serious security bugs that can be easily exploited. Further, 12 types of vulnerabilities in smart contracts are summarized in [100]. Nevertheless, it is difficult to reduce these secruity risks and vulnerabilities without automated tools due to the diverse levels of blockchain programmers. Therefore, many security analysis tools, including SECURIFY [101], OYENTE [95], or SMARTINSPECT [102], are developed to ensure high level of smart contract security for the developers [103]. For example, a decentralized smart contract system, the Hawk [104], provides a promising solution to compile a contract into a cryptographic protocol automatically. For another example, in [101], a publicly released security analyzer for Ethereum smart contracts is developed as a fully automated tool to prove whether contract behaviors are safe.

D. TECHNICAL REVIEW OF INNOVATIVE AGRICULTURAL BLOCKCHAINS

Recently, blockchain technologies have been integrated with many other advancements in IoTs, cloud computing and cloud storage to provide better services in agriculture. The convergence of blockchain and IoT, which is defined as Blockchain of Things (BCoT) in [105], has become one of the most useful frameworks in blockchain applications. In many data intensive applications, e.g., tracking and recording continuous signals from IoT devices, achieving optimized performance is challenging. This is due to various theoretical limitations and bottlenecks of blockchain. For example, conventional blockchain systems have a low on-chain speed due to their decentralized feature and consensus schemes [106]. Once the volume of real-time captured data are higher than transaction capacity, low throughput hinders the practice of blockchain technology.

Thus, many novel agricultural blockchain systems with technical innovations are proposed to ensure better integration to enhance data throughput, security and fast retrieval of the shared data in agriculture sector when keeping the main features of blockchain, i.e. traceability, immutability, and data integrity. Some key studies are highlighted in the Table 3. These studies are categorized into three areas.

First, many studies aim to improve the underlying elements of blockchain technology, focusing on the following key ideas: (1) nodes are grouped into clusters to improve the scalability of the BCoT architecture [87], [88]. In [88], Qu et. al. propose the reduction of data storage to tackle scalability related issues. It clusters the nodes into geometric groups so that data partitioning scheme can be deployed to reduce data redudancy. (2) Double chain architecture is used to store data in different types of blockchains [51], [85]. In [85] and [51], DoubleChain, a hybrid system of on-chain and off-chain data storage, is proposed to solve the throughput bottleneck. (3) smart contract filtering algorithm is designed to reduce the on-chain data. For example, in [60], a smart contract-based data filtering algorithm is proposed to build a blockchain based fish farming solution on top of a legacy database system. With the filtering algorithm, only important data are uploaded into the blockchain blocks. (4) consensus schemes that are too complex to be handled well in large IoT networks are improved to further boost blockchain performance. In [87], a Distributed Time-based Consensus algorithm (DTC) is proposed to reduce the processing overhead. While in [23], Mao *et al.* design an improved (iPBFT) scheme to make the consensus better suited for relatively higher throughput.

Secondly, combining different data storage techniques is another important strategy to tackle the exponentially increasing data storage used in many agricultural applications. Inter-Planetary File System (IPFS) is a peer-to-peer distributed data storage system in which data content is stored in distributed peers and its hash value is used to ensure data integrity [107]. The combination of IPFS and blockchain has become a popular approach to tackle the weakness of blockchain technique to store large amount of data [64], [89], [90]. For instance, as multimedia data have increased significantly in agricultural applications, IPFS has been used in [64] to store videos and images to complement with blockchain so that the multimedia evidence, including images and MPEG videos, can be stored securely to resolve rebuttals in soybean transactions. In addition, mixture with decentralized database cluster is another option to solve the high volume storage problem. In [91], Golden Seed Breeding Cloud Platform (GSBCP) is designed to ensure the safe storage of crop breeding. A decentralized database cluster is used to store the raw data collected from multiple sensors; and the database addresses and relevant metadata are uploaded into the blockchain, thus maintaining data integrity.

Thirdly, blockchain privacy and security is another focus of recent research. In many agriculture related applications, enhanced privacy and security components are added in their systems, e.g., [86], [91], [92]. In [91], the summary of breeding data is encrypted by using proxy encryption server before uploading into the blockchain. In [86], an improved partial blind signature algorithm is proposed to protect data privacy.

TABLE 3. A summary table of representative technical innovations in agricultural blockchain applications.

Paper reference	Addressed Problems	Main features	Contributions
Hang et al. [60]	Integration with legacy system used in fish farming	Smart contract filtering	Writing filtering functions in smart contract to integrate with legacy database.
Leng et al. [85]	Redundancy in the storage and privacy in agricultural transactions	Double chain structure	Two chains to enhance privacy of user information and reduce redundancy.
Lin et al. [51]	Heavy storage overhead in traceability	EPCIS, Hybrid architecture of on-chain & off-chain data.	Ingrate EPCIS as backbone and use hybrid storage to reduce on-chain data.
Si et al. [86]	Heavy storage overhead in IoTs	Light-weight IoT, Partial Blind Signature Algorithms (PBSA)	Use light-weight data for blockchain and enhance privacy by PBSA.
Dorri et al. [87]	limited scalability as blockchain consumes siginificant bandwidth overheads.	Distributed Time-Based Consensus, Clusters for reducing redundancy.	Lightweight Scalable blockchain.
Mao et al. [23]	Inefficiency of transactions when maintaining market stability.	iPBFT	Design of a new consensus scheme to improve efficiency.
Qu et al. [88]	Storage overhead increases rapidly	Grouping nodes based on their physical fuzzy distances.	A grouping overlay network storage scheme.
Salah et al. [64]	High amount of storage, e.g. video data, to solve rebuttals in soybean transactions	GTIN, IPFS	Images and records stored in the IPFS for multimedia evidences in transactions.
Hao et al. [89]	High amount of storage on real-time monitoring data in traceability system	IPFS	Real-time IoT data stored in the IPFS to keep high throughput.
Singhal et al. [90]	High volume storage of customer data for smart Know Your Customer (KYC) system	IPFS	Large amount of KYC data stored in the IPFS to solve the storage problem.
Zhang et al. [91]	High-throughput crop breeding data storage as data volume grows	Hybrid storage, Proxy encryption technology	Using hybrid storage with light blockchain.
Novo [92]	Accessibility and scalability issue when IoT devices increase.	Access control system.	Design of an architecture for scalable access in IoT.

In [92], an architecture with decentralized access control is proposed to enhance security of IoT device data.

IV. CHALLENGES AND POTENTIAL SOLUTIONS

The major technological challenges can be summarized as the following aspects: (i) scalability issue when integrating with data intensive technology, such as IoT. The throughput of blockchain is much lower than the conventional centralized databases, which can achieve tens to hundreds of thousands of transactions per second. Therefore, the data-intensive applications, e.g. monitoring and controlling farming by sensor network, require fast storage speed and low network latency; (ii) integration with existing legacy systems. Many organizations have deployed their own management systems for years and it is hard to migrate their entire systems to the emerging blockchain which could cause disruption to their current services; and (iii) security and privacy. Blockchain encourage the decentralized infrastructure which increases the data transparency but compromise the data privacy. Although most recent blockchain platforms allow the uploading of encrypted transaction records on-chain, more security features would enhance the data security and privacy to a higher level due to various types of attacks [108]. Based on the technical innovations discussed in the previous section, the potential solutions for solving these challenges are summarized and illustrated in Figure 5.

As illustrated in Figure 5a, the use of a hybrid architecture solution by combining centralized databases or other data storage systems with blockchain is proposed in many studies [85], [91], [109], [110]. Although some applications focus on designing light-weight data structure to reduce the on-chain data amount [51], [86], the mixture and links of blockchain with other storage systems, such as IPFS, provides a more scalable and sustainable way to deal with the exponential increase of data that most modern storage solutions are facing. The hybrid architecture can solve the demand of high throughput data storage requirement while maintaining data integrity.

Integration with legacy systems is another challenge when promoting blockchain technology in agricultural organizations. In [13], it is highlighted that the blockchain systems are difficult to seamlessly integrate with legacy systems. We believe that the popular use of cloud services in most enterprises could potentially solve this issue. As illustrated in Figure 5b, when data from legacy systems in individual companies are uploaded in cloud services, service providers can easily extend their services to blockchain based systems if any business needs are proposed between multiple parties. In addition, the organizations could save the cost to enhance data privacy and security as the risks could be efficiently controlled and managed by the service providers.

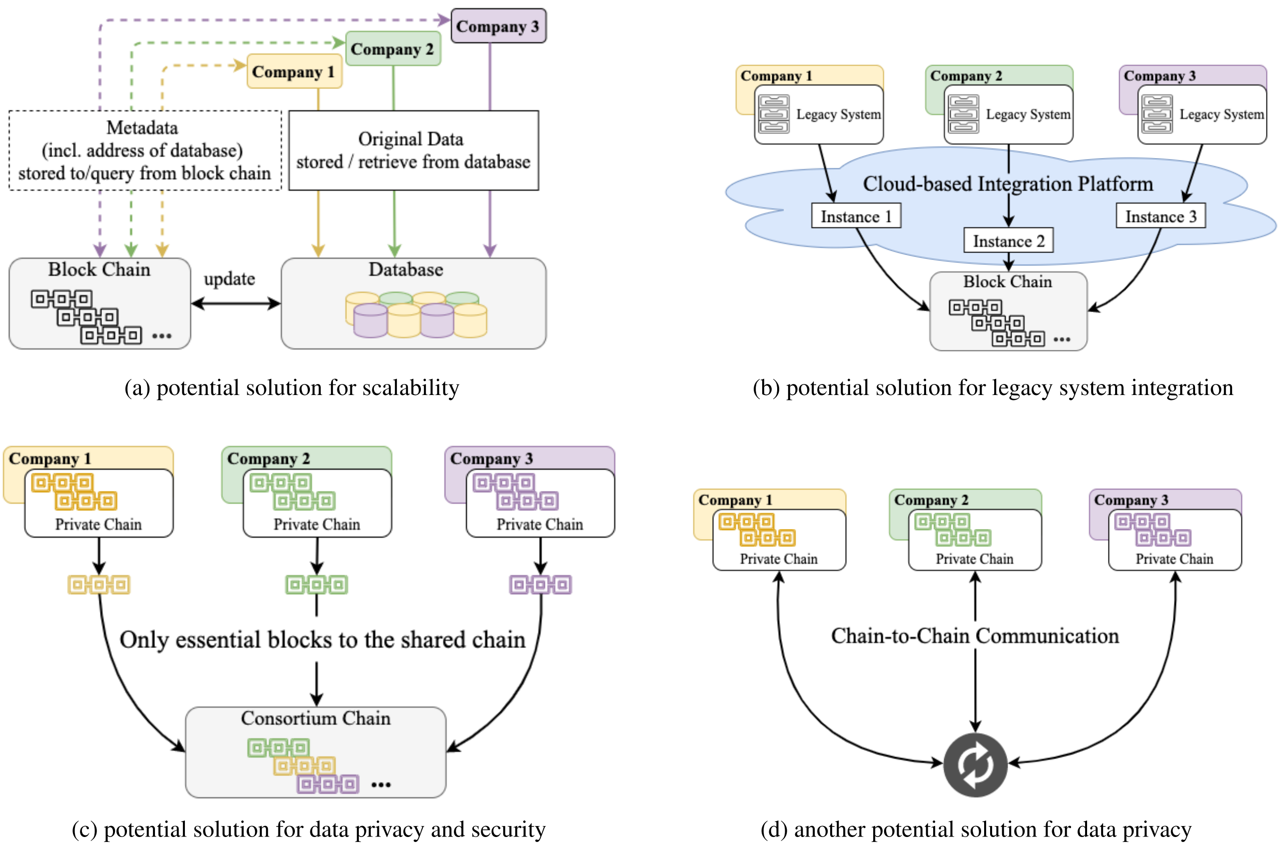

FIGURE 5. The alternative solutions to target on several challenges in state-of-the-art frameworks.

To further enhance blockchain privacy and security, an infrastructure level solution is more suitable for tackling the challenge. As illustrated in Figure 5c and 5d, two types of blockchain structure changes could potentially enhance data privacy and security. In Figure 5c, a hierarchical blockchain based system is proposed as the private blockchain has better characteristics to maintain data privacy. Only data required by legislation or regulation bodies are stored into a consortium blockchain. Figure 5d offers another enhanced version in Figure 5c. It uses efficient chain-to-chain communication technology to remove the consortium blockchain, thus further maintaining data privacy in private blockchains. Of course, the communication scheme across multiple private blockchains need be secured as proposed [111].

In addition to these technical challenges, there are other challenges in environmental, social and organizational aspects [112] to promote blockchain technology in agricultural sector. There are still lack of regulatory and legal requirements to reinforce the deployment of blockchain based systems. Thus, some enterprises are reluctant to adopt the technology if their current systems can satisfy their business needs. Further, it requires knowledge and skills on both agriculture and blockchain to develop these applications. However, it is predictable that the use of blockchain to build trustable systems would be predominant in many countries and these challenges would need to be addressed in near future [113].

V. AN ILLUSTRATION OF ESSENTIAL FOOD SUPPLY IN POST-COVID-19 PANDEMIC

In this section, we present an illustration to demonstrate a blockchain based food supply chain management system in agricultural applications. The ongoing COVID-19 pandemic has brought a huge crisis on the global food supply [114] despite many existing blockchain systems in agricultural supply chain. During this period, shortage of essential food, such as rice, fresh vegetables, flour, and eggs, has caused panics among suppliers and shoppers due to disruptions in supply networks. Producers, manufacturers and distributors have limited information when customers' shopping behaviours change abruptly. It takes weeks, even months, to adjust resource allocation in order to recover the operations of food product supply to a normal level. Further development of blockchain based supply chain systems is required to improve the situation by tackling issues related to asymmetric information.

There are at least three key lessons that we could learn from COVID-19 related global food supply disruptions. These include: (1) we need real-time accurate information

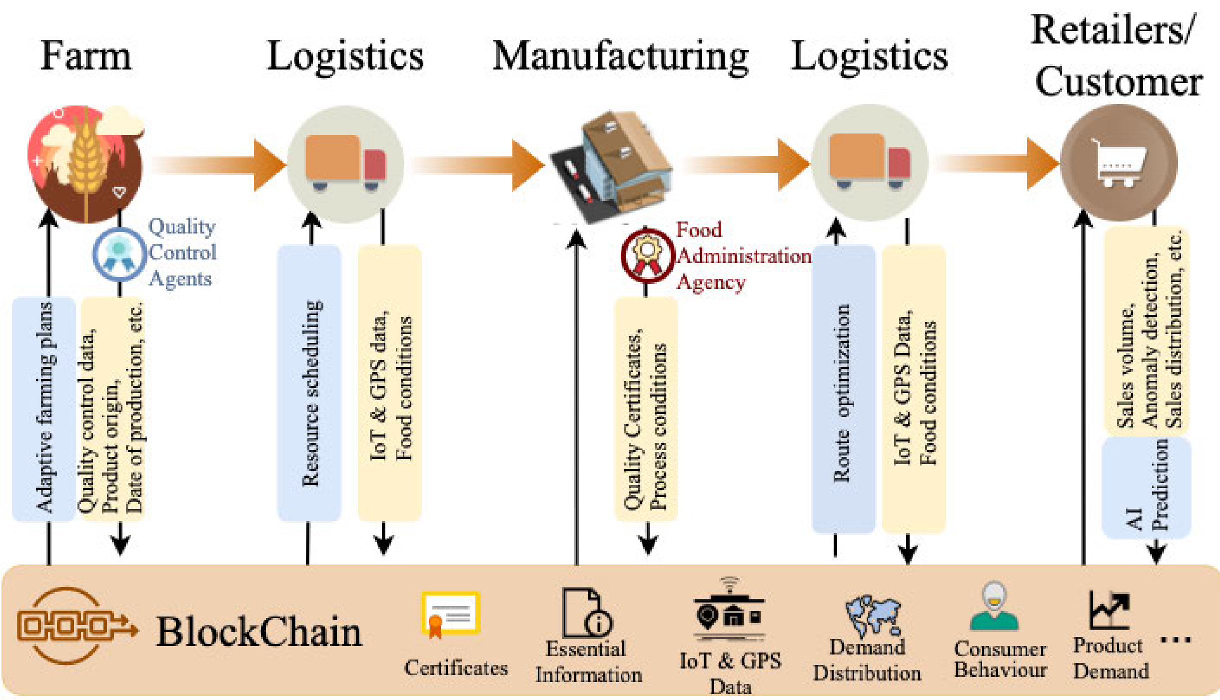

FIGURE 6. Use Case - Improved post-COVID-19 blockchain based supply chain solution.

for parties involved. When panic buying occurs, the supply network lacks of accurate information to reflect the purchase behaviours, thus making quick responses impossible. (2) More efficient coordination among parties at a global scale is necessary in order to generate quick and appropriate responses in real-time. (3) Efficient process is needed to reduce time in bureaucracy procedures. These lessons motivate us to reform the existing blockchain based supply chain systems to provide better services in future.

As shown in Figure 6, we illustrate an improved blockchain based supply chain system that can be deployed in post COVID-19 era. The blockchain technique will be seamlessly integrated with machine learning methods to achieve a more efficient system. Like other existing blockchain system, the provenance of products, including essential information and certificates, is stored in the blockchain for traceability. In such a system, retailers are information consumers not providers. In this improved system, the main distinctive and unique feature is the integration of retailer and customer data into the blockchain. Insight analyses of key weaknesses of current supply chain management systems have identified that the involvement of these retailer/consumer data is valuable to boost the effectiveness of the blockchain based system. If shopping data can be uploaded into the system, up-chain parties, including producers, manufacturers and logistic companies, could explore these data for better coordination and resource allocations. Thus, a closed loop could be formed when retailers/customers' data are stored into the blockchain. The main features are highlighted as follows.

Using AI based retail sales prediction to reduce on-chain data. Retail forecasting has offered an oppotunity to optimize retailers' planning to maximize their profitable margins by setting reasonable inventory level based on popularity of products [115]. Recent research has shown some extent of success in product-level demand forecasting at a high granularity level. The demanding prediction of products can be integrated as a filtering method to reduce on-chain data of the proposed blockchain system.

Algorithm 1 Data Registration Function in RetailerData Smart Contract

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Input: Message sender (msg.sender), authentification list (AL) of retailer units, product object (p) including all sales infomation of the product, current time (t).
Output: Data registered

if msg.sender $\in$ AL && $abs(p.real\_sale - ai\_module.predict()) > th$ **then**
  $register(msg.sender, p, t)$
else if msg.sender $\in$ AL **then**
  $register(msg.sender, p.id, normal\_flag, t)$
else
  Revert contract state and show error
end if
return p

In Algorithm 1, the pseudocode of data registration function in RetailerData smart contract is used as an example to show how data collected from retailers can be uploaded on the blockchain system. Here, the AL refers to the authentized list that all registered retailer units can upload their data to improve the up-chain strategical optimization, and the *p* refers to individual products that supply process need to be optimized. With an AI module filtering normal sales prediction, the on-chain data can be reduced significantly. At the same time, any anomaly or significant customer behaviour changes are recorded into the blockchain so that up-chain parties could explore the data for efficient planning.

The blockchain retailer data facilitate better planning and operation of upchain stakeholders, such as suppliers, manufacturers and logistic companies. As illustrated in Fig. 7, up-chain parties could request these retailer data to feed into their AI modules to optimize their planning and operations. For examples, logistic companies could request data of retailer units and their demands of products to make routing optimization based on the geographic distribution of demand; manufacturers could use the data to adjust their raw material processing to meet urgent market demands; and farmers could make better planning for future productivity.

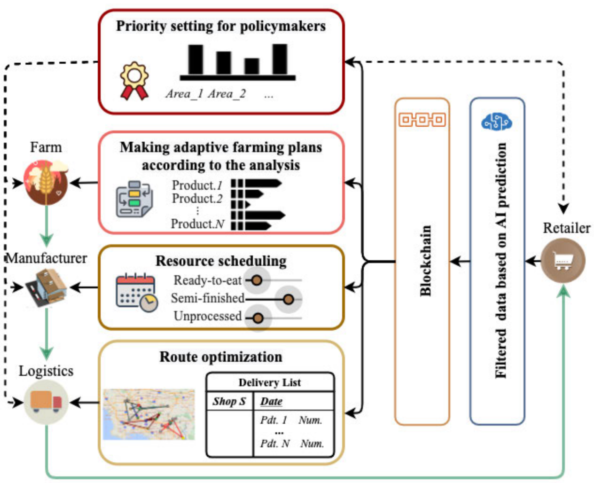

FIGURE 7. The retailer/consumer data are important to improve efficiency of the food product supply chain.

The blockchain retailer data improve work priority of government and regulation bodies. As illustrated in Fig. 7, once government and regulation bodies have the permission to access regional data on demand, policy makers could set priorities and coordinate with all involving parties more efficiently to deal with unexpected events like COVID-19. Further, as shown in Fig. 6, quality control agents and food administration agency could work closely with producers and manufacturers so that a lengthy quality monitoring and auditing process can be simplified.

VI. DISCUSSIONS AND CONCLUSION

Blockchain technology, as a part of the emerging e-agriculture system, is reshaping the whole sector to solve food crisis in new century. It plays key roles from the farm to the folk in many aspects: it ensures data privacy and integrity by combining smart farming and precision agriculture techniques to improve farm productivity; it creates a more efficient food supply chain by establishing trust among involving parties, thus simplifying the process; and the last not the least, it enables farmers to maximize their profit via a trusted platform. Overall, it adds great values to all stakeholders in the entire agricultural sector.

In this paper, to promote blockchain techniques, especially their various uses in the ecosystem of agricultural products, we have presented a comprehensive survey on current blockchain based agricultural applications and innovations. We have explained various concepts of blockchain technology, including its data storage ecosystem and its several popular application platforms. We have offered a detailed investigation of desperate blockchain applications in the agricultural sector. Then, we have considered several key challenges in the current use of blockchain related technologies in agricultural applications and provided some possible solutions. These challenges include: (1) scalability, (2) integration with existing legacy systems, and (3) security and privacy. Simply put, our suggested solutions can be viewed in a holistic fashion as a redesign of the system architecture. Further, we have indicated possible future developments and applications of blockchain in this sector via an illustration, i.e. the current COVID-19 global food crisis. In future, we wish to provide further discussions on various aspects of blockchain and explain in detail how current challenges as indicated in this paper can be resolved in future development of blockchain in agricultural systems. Potentially, our illustration could be further extended to be a much fuller case study, which could then be evaluated via a series of emperical tests.

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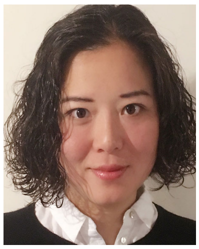
WEIJUN LIN is currently the Deputy Director of the Institute of Agricultural Economics and Rural Development, Guangdong Academy of Agricultural Sciences. He has presided over or participated in more than 30 scientific research projects. He edited five books, published more than 30 articles, and one computer software copyright. He holds three invention patents. His research interests include agricultural industry economics and planning, agricultural product quality safety and circulation, intelligent supply chain management, and targeted poverty alleviation. He is also the Executive Director of the Guangdong Provincial Academic Association of Rural Economy, the Deputy Secretary-General of the Guangdong Provincial Academic Association of Science and Technology Information, and the Director of the Monitoring and Early Warning Branch of the China Association of Agricultural Science Societies.

XINGHONG HUANG is currently the Director of the Information Research Office, Agricultural Economics and Rural Development Institute, Guangdong Academy of Agricultural Sciences. He is mainly engaged in agricultural science and technology consulting, and agricultural information technology research. He has presided over seven provincial scientific research projects, published 17 articles as the first author, and participated in the compilation of two monographs. He also obtained more than ten national computer software copyrights and applied for two invention patents. He is also the Executive Director of the Provincial Agriculture and Animal Husbandry Information Society.

HUI FANG received the B.S. degree from the University of Science and Technology, Beijing, China, in 2000, and the Ph.D. degree from the University of Bradford, U.K., in 2006. He is currently with the Computer Science Department, Loughborough University. His research interests include computer vision, image/video processing, pattern recognition, machine learning, deep neural networks, data mining, scientific visualization, visual analytics, and artificial intelligence.



VICTORIA WANG received the bachelor's and Ph.D. degrees from Swansea University. She is currently a Reader on Security and Cybercrime with the Institute for Criminal Justice Studies (ICJS), University of Portsmouth. She is the Principal Investigator of the EPSRC project Data Release—Trust, Identity, Privacy Security (EP/N027825/1) (2016—20). She is an Investigator of several HM Government-funded projects, including Cyber Security Breaches Survey (2016—19), Victims of Computer Misuse Crime (2018—19), and Understanding the UK Cyber Skills Labour Market (2019). Her current research interests include cyber-security and information security management, social theory, and theoretical criminology, in particular, security threats and management measures in organisations and cybersecurity in various countries, such as Nigeria, South Korea, and Vietnam, and networks, such as the Darknet.

YINING HUA received the B.Sc. degree in information security from Northeastern University, Shenyang, China, in 2016. She is currently pursuing the Ph.D. degree in computer science with Loughborough University. Her research interests include computer networks, especially distributed systems, edge/fog computing, and information-centric networks.

JINGJIE WANG is currently working as an Assistant Researcher with the Agricultural Economics and Rural Development Institute, Guangdong Academy of Agricultural Sciences. He has mainly participated in the Key Research and Development Plan of the Ministry of Science and Technology, the Opening Project of the Key Laboratory of Agricultural Products Storage and Preservation of the Ministry of Agriculture and Rural Affairs, the Construction Project of the Modern Agricultural Industrial Technology System, and the China-Serbia Intergovernmental Cooperation Project. His research interests include the agricultural Internet of Things and agricultural infomatization.

HAINING YIN received the B.Sc. degree from Shanghai University, in 2000. Since 2000, he has been working with Sybase Inc., which was merged with SAP, in 2010. He is currently working as a SAP HANA and Machine Learning Expert with SAP China. He is also a Business Architect with the SAP Centre of Excellence. He has more than 15 years of machine learning and big data solution experience. His current research interests include machine learning, data analytics, data mining, and blockchain.

DEWEI YI (Member, IEEE) received the B.Eng. degree in software engineering from the Zhejiang University of Technology, Zhejiang, China, in 2014, the M.Sc. degree from the Department of Computer Science, Loughborough University, Loughborough, U.K., in 2015, and the Ph.D. degree from the Department of Aeronautical and Automotive Engineering, Loughborough University, in 2018. He was a Research Fellow with the Warwick Manufacturing Group (WMG), University of Warwick, U.K., in 2019. He is currently a Lecturer with the School of Natural and Computing Sciences, University of Aberdeen. His current research interests include trustworthy autonomous systems, personalized driving assistance, autonomous vehicles, and vehicular networks.

LAIHUNG YAU received the M.B.A. degree from Murdoch University. She established Guangzhou Feijie New Telecommunication Ltd., in 1999, and Blue Profit Ltd., in April 2016. She is currently the Co-Founder of Asia Pacific Applied Nano Technology Research Centre Ltd., Hong Kong. She has more than 20 years of experience in investment management of enterprises and committed to promote the applications of new technologies, such as AI and blockchain. Since 2000, she has been the Deputy Secretary of the GuangDong Foreign Investment Law Society. Since 2013, she has been the Deputy Secretary of the Guangdong Big Data Association.