Journal of Cleaner Production 316 (2021) 128254

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Blockchain for sustainable e-agriculture: Literature review, architecture for data management, and implications

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ARTICLE INFO

Handling Editor: Dr. Govindan Kannan

Keywords:
Blockchain
Internet-of-Things
Smart function
e-agriculture
RAFT Consensus
FAIR data Principles
Distributed ledger technology

ABSTRACT

The architecture design by integrating the blockchain and IoT has gained salience in information systems and information technology research. However, there has not been significant work on the comprehensive and sequential applications of blockchain integrated IoT in e-agriculture for data validation, data storage, data security and data privacy. We aim to bridge this gap in the literature and discuss how the integration of blockchain and IoT can improve backward and forward linkages in agricultural value chains, benefit value chain actors, and augment the performance of IoT network. The study considers use cases of agriculture inputs and commodities/products to demonstrate the application of IoT devices in data collection and blockchain technology for data validation, data storage, data security, and data transmission. RAFT consensus algorithm for permission blockchain and FAIR principles are utilized to make e-agriculture information systems decentralized, efficient, fault tolerant, and interoperable. The technology coupling in e-agriculture can create externalities such as shared benefits, improved coordination between value chain actors, and real-time decision-making for optimal resource allocation and their sustainable utilization in e-agriculture.

1. Introduction

Information and Communication Technology (ICTs) play a vital role in electronic Agriculture (hereafter e-agriculture) (Andreopoulou, 2012; Bartlett et al., 2015) as efficiency and process control in agriculture is inextricably linked with the use of ICTs (Lehmann et al., 2012). Walter et al. (2017) define e-agriculture as the manifestation of ICTs, crops, and livestock production systems, their diversification, and the agri-food actor-networks involvement. They opine that the improvisation in agriculture data collection, data storage, and data transmission through verifiable transfer mechanisms and regulated transparency functions can impact sustainable agriculture. UN-FAO defines e-agriculture as the “conceptualization, design, development, evaluation, and application of new or innovative ways to use emerging or existing ICTs.” In collaboration with the ITU, FAO launched Asia-Pacific ICTs studies to develop a policy guide for advancing the national e-agriculture strategy (FAO, 2016). It suggests that e-agriculture infrastructure embraces the confluence of ICTs and blockchain technology (Tripoli and Schmidhuber, 2018). However, the current agriculture information systems in developing and least-developed countries lack the trusted permission platforms to access or retrieve authentic agricultural data. The existing systems are prone to data tampering and cyberattacks as different silos of data are curated by diverse upstream and downstream value chain actors, namely producer, processor, wholesaler, retailer, and consumer (Bloom et al., 2014). The data generation process is often subject to duplication or double entry problems (Nakasumi, 2017). If the record is changed in one silo, this may not be reflected in another silo.

To address this problem, the integration of blockchain technology and internet-of-things (IoT) has recently gained salience to ensure data rights and defend data duplication. It can solve the double marginalization problem reducing information asymmetry (Nakasumi, 2017) and tracing bio-physical resources for use or reuse in the large-scale dataset (Nobre et al., 2016). The architecture design integrating the blockchain and IoT has received attention in information systems research. Torky and Hassanein (2020), summarizing the benefits of the integration of blockchain and IoT, enumerate a few critical supply chain processes in e-agriculture: (1) data recordings like the farm, farmer, soil, and water data, (2) data monitoring to track purchases, orders, updates, receipts, and shipment notifications or other trade-related transactions, verifying food products (complying with fair trade practices), (3) assigning and linking agricultural produce to QR codes, serial codes, digital tags like RFID, and (4) data sharing for disseminating information about crop

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https://doi.org/10.1016/j.jclepro.2021.128254
Received 29 September 2020; Received in revised form 24 June 2021; Accepted 7 July 2021
Available online 10 July 2021

production practices, manufacturing procedures, delivery, assembly, and maintenance of agricultural products with suppliers, and vendors (Torky and Hassanein, 2020, p. 11). Nonetheless, there is paucity of empirical work on the comprehensive application of blockchain integrated IoT in e-agriculture for data validation (Huang et al., 2020), data storage (Pahl et al., 2018), data security and privacy (Wilkinson et al., 2016; Ferrag et al., 2020). Privacy is a central issue to data control and protection as the divergent actors' attitudes to privacy can create tension in the development of blockchain technology and its integration with IoT (Renwick and Gleasure, 2020). The theoretical or empirical work revealing the amplification of such technology integration for data validation, storage, and privacy has been quite sparse. This study, therefore, aims to explore this key issue in the backdrop of the research problem that how blockchain technology and IoT coupling can improve backward and forward linkages in e-agriculture, potentially benefit value chain actors, and augment the performance of IoT networks. This paper raises two specific research questions (RQ_s).

- **RQ_1**: How does the integration of blockchain and IoT improve data collection, data validation, and data management in e-agriculture?
- **RQ_2**: How can the blockchain integrated IoT architecture enhance capabilities and real-time decision-making of agri-value chain actors to transform conventional or traditional agriculture into a smart farming system and translate into sustainable e-agriculture?

This study considers use cases of agriculture inputs, namely seed, fertilizers and pesticides, and agri-produce to demonstrate the application of IoT network devices for data collection and the application of blockchain technology for data validation, data storage, data security and data transmission. RAFT consensus in-built permission blockchain and FAIR principles are adopted to make e-agriculture information system decentralized, efficient, scalable, fault-tolerant, and interoperable.

This paper makes three important contributions to the growing body of literature. First, the study elucidates the potential of blockchain technology solutions to strengthen backward and forward linkages, and integrate the product flow, information flow, and cash flow in agricultural value chains. The technology-enabled backward and forward linkages in e-agriculture can create positive externalities like shared benefits, improve coordination between value chain actors, strengthen capabilities, and effectuate real-time decision-making of actors for optimal resource allocation and utilization in production, harvesting, storage, processing, distribution, export, and by-product management. This can eventually make the farming system integrated, profitable, and sustainable.

Second, the study addresses myriad challenges encountered in agriculture data collection, data validation, data security, data storage, and data transmission by harnessing the potential benefits of technology-coupling. And it can eventually transform the agricultural information system decentralized and strengthen information governance or e-governance in e-agriculture. This study offers a potential scope for data control and protection by hiding the transaction related information of value chain actors (senders and receivers) and their magnitude through the application of RAFT consensus algorithm and improvised security system. As scalability and interoperability has raised serious concerns for blockchain technology adoption, the use of Artificial Intelligence and Machine Learning (AI-ML) modules is proposed in the architecture to counter this shortcoming.

Third, the consideration of a hybrid digital platform proposed in blockchain–IoT architecture can influence in networking of farmer collectives, agribusiness firms, agri-tech start-ups, certification standards organizations, regulators, and financial institutions, among others, and foster trust or manage the contract and negotiation processes in the agri-food domestic and export trade.

The remainder of the paper proceeds as follows. Section 2 presents the extant literature review. Section 3 presents the research design and methodology. Section 4 elucidates blockchain-enabled data collection, followed by data validation, data security, storage, privacy, and data sharing in Sections 5, 6, and 7. Section 8 presents the blockchain architecture. Section 9 presents discussion and conclusions. Section 10 presents the managerial and policy implications.

2. Literature review

Blockchain integrated ICTs gain salience in the-agriculture supply chain traceability, data provenance, interoperability, immutability, and auditability (IBM, 2015; Swanson, 2015; Kamble et al., 2020). The review summarises the application of blockchain technology in e-agriculture and identifies the research gap based on the review concerning the data collection and their management. To review the relevant studies conducted in the realm of sustainable e-agriculture, a sequential search is performed with keywords, namely "Blockchain technology" OR "Smart Contract" AND "ICTs" AND "e-Agriculture" AND "Sustainability"; "Blockchain" AND "IoTs" OR ("Data Collection" AND "Data Storage" AND "Data Security" AND "Data Privacy") on the Google scholar and existing search databases, viz. Science Direct, Wiley, and Ebscohost, and Proquest, among others. The search locates as many as 1, 450 articles in Google Scholar, Scopus, and Web of Science (WoS). Excluding books and book chapters, editorial, conference proceedings, and low ranked journal articles, 75 papers are considered for review relevant to the integration of blockchain and IoT for smart farming or precision agriculture.

The literature review is organized into three sub-sections: the first sub-section elucidates pros and cons of blockchain technology in e-agriculture. The second one reviews relevant literature on the integration of blockchain and IoT in e-agriculture data collection and management. The third one focuses on blockchain and e-agriculture information systems.

2.1. Promises and pitfalls of blockchain technology

Blockchain technology is interoperable with IoT or wireless sensor networks (Sun et al., 2016). The integration of blockchain technology and IoT can augment autonomy and intelligence in farm management. Blockchain can make IoT communications more secure, transparent, and tamper-proof. This can further improve digital agricultural processes with real-time data monitoring in accelerated end-to-end transaction processes. In other words, blockchain technology can enhance the security and performance of IoT networks in e-agriculture through its peer-to-peer network (Torky and Hassanein, 2020). Second, blockchain technology can strengthen data collection and data management and improve government service integrity (Walport, 2016). Lin et al. (2017) opined that production and environmental data stored in the distributed cloud platform fortifies smart farming information systems. Also, blockchain-enabled e-services have emerged as a commonplace for promoting ecological data monitoring and use (Gouveia and Fonseca, 2008). Third, convenience analysis suggests that blockchain-integrated IoT can significantly improve farmer crop production systems, input purchasing options, and revenue management (Li et al., 2020). Fourth, technology integration can enhance-agriculture market efficiency, improve food quality, safety standards, and supply chain traceability (Lin et al., 2017; Kamilaris et al., 2019). This can mitigate the institutional risk and uncertainty in procurement, processing, and distribution, promote regional agri-food economies, and contribute to Sustainable Development Goals (Lin et al., 2017). Nonetheless, Walter et al. (2017) cautioned that sustainable development in agriculture can only happen with the proactive development of technology policies supporting the necessary legal and market infrastructure and inclusive participation of value chain actors. Li et al. (2020) also noted a few challenges concerning blockchain application in smart farming that include optimal use of technology or scalability related to latency (Lezoche et al., 2020; Zhao et al., 2019), high technology entry threshold, network threats for application security, the likelihood of network paralysis and synchronization time for processing transactions (Reyna et al., 2018). Also, cost structure, high consumption and increased skillsets demands of blockchain use have been seriously critiqued (Wang et al., 2019a; Sander et al., 2018; Zhao et al., 2019).

In traditional e-agriculture, a few challenges weaken the potential of blockchain technology application as experienced by AgriDigital in execution of blockchain-enabled commodity management platform. The challenges include, namely matching the physical commodity to the digital, legitimate certification system, connectivity with farmers and trading agencies, and incentives, and cooperation related to “efficiency gains, improved liquidity, and data provenance to ensure decision-makers buy-in” the commodity supply chain network (Sylvester, 2018). Sylvester (2018) suggests that self-execution of smart contracts and automated payment system can formalize agriculture insurance products and create a real-time risk management system.

2.2. Integration of blockchain and IoT in e-agriculture data management

Why the technology integration or technology-coupling is important? It is apparent from the literature review that the IoT-based system works on an ineffective centralized system, and it becomes difficult to reconcile different data sources available to various platforms (Pahl et al., 2018). Further, data ownership infrastructure compounds data access problems. The action nodes in the distributed architecture can secure the system and create a single pool of data shared among the agricultural value chain actors. This eliminates a single point of failure in the transaction, thereby, increases data collection accuracy, secures data storage, and transforms farm organization and governance (Davidson et al., 2016). An affiliated technology of blockchain called smart contract can form a peer-to-peer network in e-agriculture and facilitate, verify, execute, and enforce transactions. In that agricultural value chain actors can share and retrieve real-time data. In other words, blockchain can influence the data democratization process in e-agriculture and enhance the participation of complementing actors to digitize physical assets into digital information assets (Chen et al., 2020).

Blockchain technology enables data security through ‘decentralization’ rather than ‘security of obscurity’ (IBM, 2015). Data stored in servers centrally, as in the IoT-based system managed by the administrator, is vulnerable to data loss or distortion. As the distributed database helps data-driven mobile applications for optimal farm management, blockchain technology can create a secure, scalable, and resilient infrastructure for IoT and existing ICTs used in smart farming and precision agriculture. It comprises a set of technologies combining sensor devices, cloud-based information systems enhanced machinery and informed management to optimize production by accounting for variability and uncertainties in agricultural systems (Gebbers and Adamchuk, 2010).

Blockchain-based data management promotes profitable and eco-friendly agri-enterprises. This can help in environmental data monitoring (soil, water, weather, and climate) and serve farm value chain actors (Walter et al., 2017). For example, several smart farming models have implemented blockchain IoT-based architecture in e-agriculture. Patil et al. (2017) designed a lightweight blockchain-based architecture for smart greenhouse farms in that IoT sensors act as a private local blockchain that farm owners centrally manage. Lin et al. (2018) proposed a blockchain-IoT-based smart agriculture framework–the core of the framework establishes trust between the actors using blockchain. Agents of products from plantation to sale can access data stored in the blockchain through android/iOS operated smart telephony. Iqbal and Butt (2020) designed a blockchain-based transparent farm management system. Munir et al. (2019) developed a secure and intelligent smart watering system using fuzzy logic and blockchain for data privacy and reliability. Bordel et al. (2019) devised a blockchain (Ethereum)-based water control system to reduce water waste or automatic irrigation management. For agriculture data integrity, Hang et al. (2020) developed a secure fish farm platform using Hyperledger Fabric blockchain. Using a multichain platform, Ferrer (2018) demonstrated that robots’ swarms could deliver in precision agriculture with distributed decision-making. Lin et al. (2017) proposed the blockchain architecture for adoption at the local and regional scale. Each actor can obtain permission to access real-time water quality data stored in the blockchain. Farm organizations and the national government also use blockchain to make their farming practice smarter and interactive. For example, Farmland irrigation associations in Taiwan have utilized blockchain to archive and store data for public use (Lin et al., 2017). Li et al. (2020) showed that the application of blockchain technology to fresh commodities, whole grains, and aquatic products has statistically improved the degree of convenience compared to valuable and fragile commodities. They conclude that sustainable e-agriculture brings greater convenience to farmers’ sales and marketing decisions, increasing twenty-five percent as compared to traditional e-agriculture.

2.3. Blockchain and e-agriculture information system

To promote inclusive participation in e-agriculture, blockchain can help diverse stakeholders such as farmers to exchange production-related information, establish cooperation, peer-review. This can develop an informal information system to complement the regulatory authorities’ formal information system (Walter et al., 2017). The information flow among farmers and agri-value chain actors can be scale-independent, while the benefits appropriated by the actors should be equitable. Chen et al. (2020) proposed a blockchain-based e-agriculture framework incorporating the farm’s circular agricultural model into blockchain application. The study illustrates that the blockchain network automatically collects and uploads production and environmental data through smart devices (IoT and WSN) for external sharing. The smart farming system can promote “digital agricultural democratization” by addressing information asymmetry and improving traceability and secure transactions between the value chain actors.

2.4. Research gap

It is evident from the literature review that there has been a significant advancement in blockchain integrated IoT-enabled data collection and data management in the smart farming system. However, there is a scope of further research on blockchain-enabled data validation, data security, data storage, and data sharing, especially for two reasons. First, the diverse agri-value chain actors along the stages of the value chain generate and share myriad data. The traditional ways to manage data in a centralized fashion are prone to inaccuracy, data distortion, misuse, and cyber-attacks in various forms, viz. data attacks, network and equipment attacks, supply chain attacks, and other relevant attacks (Gupta et al., 2020). Second, a smart agri-value chain network utilizes existing and emerging ICTs such as IoT or sensor devices and machine learning to collect and process data (Singh et al., 2020). So, there is a need to integrate blockchain and IoT applications for backward and forward linkages in e-agriculture. This can be doable by storing and managing data generated by diverse actors in a peer-to-peer network and through the effectuation of a smart contract (Ali et al., 2018). And this issue has been addressed by designing a five-stage holistic process from data collection to data transmission in e-agriculture, described in the methodology section. The research gap as is elucidated through the extant literature review has stimulated the authors of this study to unravel how the integration of blockchain technology and IoT can improve data collection, data validation, and data management in e-agriculture. Secondly, the research gap provides a clear direction to demonstrate how blockchain-integrated IoT architecture would enhance capabilities and strengthen agri-value chain actors’ decision-making to transform conventional agriculture into a smart farming system or precision agriculture.

3. Research design and methodology

The research design adopted in this study presents a flowchart of how the two research questions are being explored. This section describes blockchain typology and operational mechanisms for data collection, data storage, and data sharing in the subsequent sub-section. As can be seen in Fig. 1, blockchain technology application for e-agriculture comprises of five stages, which include: (1) data collection, (2) data validation, (3) data security, (4) data storage, and (5) data transmission/sharing through external Application Programming Interfaces (APIs).

1) Data collection

There are four types of data monitored and collected by IoT or sensor devices: environmental data, production data, administrative data, and supply chain or external agency data (Gouveia et al., 2004; Jagannathan and Priyatharshini, 2015; Xiong et al., 2020).

When smart farming and precision agriculture are discussed, agri-based IoT devices can help farmers with real-time information about lands and crop parameters. The agri-based IoT devices are extensively utilized to collect real-time field-based and/or farmer-level data. Agri-based sensor devices allow farmers to know real-time information about soil, water, and crop quality and help them integrate it with blockchain technology to obtain digital information assets. Also, fish farmers use IoT sensors to track real-time activities and parameters of ponds and fish or fingerlings. Agriculture 4.0 allows blockchain scripts/codes to run within as the small JavaScript, IoT devices can easily make specific decisions or trigger an event when a condition is not fulfilled that is specified in the smart contract (Linsner et al., 2019). IoT devices can communicate with each other for the extensive farmland to broadcast transactions between IoT devices and sharing the results into the blockchain. Even electro-optic sensors can detect weeds, herbicides, and other unwanted plants that retard crop development. Farmers growing organic produce can use optical sensors to measure soil organic matters, moisture levels, minerals, pesticides, etc. The IoT-based fertilizing technique can help accurately identify spatial patterns of nutrients required in soil and substitute labour requirements. In aquaculture, wherein many fish tanks are used for a breeding school of fish, an array of IoT aqua sensors can communicate to know patterns and fish movement in the tanks. There can be a trigger if there is any deviation in the fish movement pattern. This way, fish farmers can get real-time information from data collected using an array of IoT sensors and stored in a blockchain that monitors the growth or development of fishponds/tanks (Torky and Hassanein, 2020). There is a growing interest in IoT-based applications in smart cities development also, and such examples can help dovetail data collection and management in e-agriculture with regional development of agri-food networks (González-Zamar et al., 2020).

2) Data validation

Real-time data collected in the data collection layer passes through a pre-defined standard operating procedure of smart function where data validation takes place. If validation fails in this stage, the error library triggered the output by popping up the exact reason for failure and the process gets terminated.

3) Data security

Validated data enters the security layer and for data processing, one needs to identify a correct public or private key, SHA decryption, and encryption algorithm. Hence, a unique hash identity code gets generated, and as per the fault tolerance algorithm, data are forwarded to data storage layer.

4) Data storage

Validated data are further appended in relevant crypto-graphical blockchain nodes of the peer-to-peer network in a standard or graph database (Holzschuher and Peinl, 2016). In the case of failure at any decision process, the block gets terminated and is triggered relevant output with the end process (Xie et al., 2017).

5) Data Transmission

When data are shared with external agencies, blockchain utilizes a Resource Description Framework (RDF) (Brickley et al., 1999) linked to

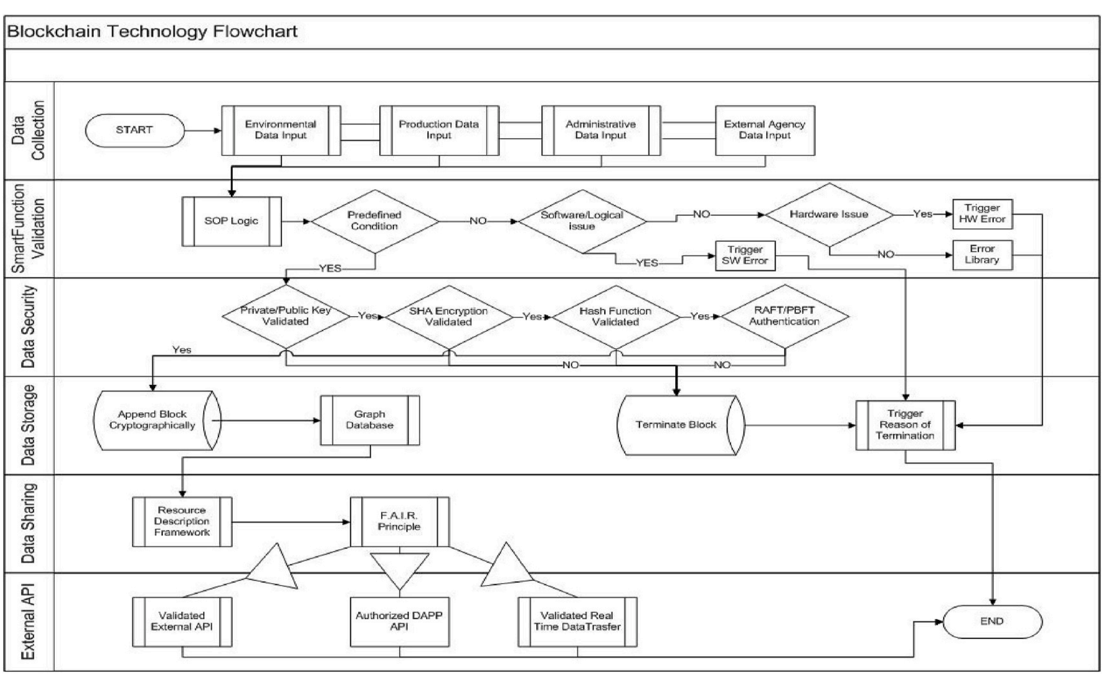


Fig. 1. Research design flowchart.

a graph database. This helps to transact multiple queries at a time and increase the speed of response to queries. FAIR guiding principles can make blockchain integrated IoT platform data compliant (Wilkinson et al., 2016). Data are shared with a controlled formula to external APIs including Decentralized Application (DAPP). Description of each stage, costs or risks involved and potential benefit of blockchain in e-agriculture is presented in Table 1 below.

3.1. Blockchain typology and operational mechanisms

In agri-value chains, chain traceability depends on how data are collected, validated, secured, and stored in the blockchain. With the-agriculture product flowing through different processes, data, and information flow in parallel. Input parameters, namely seed, fertilizers, and pesticides, irrigation, machinery, farm management, pass through various processes to obtain the output, such as quality product, nutrition, greenhouse gas emission level, among others from the value chain (refer to Fig. 2). There are two types of blockchain, namely permissionless and permission (refer to Table 2). A blockchain platform can be public or private based on a blockchain consensus mechanism. The consensus mechanism can be the Proof of Work (PoW) and Proof of Stake (PoS) for permissionless blockchain, while it can be the RAFT consensus for permission blockchain. Storing data either in the relational database (SQL/NoSQL) or graph database can help process query management and data access.

APIs can be the Resource Description Framework (RDF) for permission blockchain. It is compatible with the graph database and can yield results with data properties to "defend data" stored in the blockchain.

The consensus mechanism, fault tolerance nodes, immutability nature of blockchain-stored data allow the decentralized ecosystem to foster trust among the actors. At the time of dispute resolution between the actors, the system traces data at a particular point through time travel study. It helps restore transparency between the actors who are part of the peer-to-peer network and eliminates reliance on the third-party or intermediaries. Besides, smart function's intelligent nature with various security layers added to data in blockchain eliminates the potential threat of cyber-attacks. The fault tolerance algorithm ensures no single point of failure (Davidson et al., 2016). For data security, permission blockchain scores over the permissionless blockchain as the former one follows the RAFT consensus algorithm for validation and uses a graph database for storage (Clow and Jiang, 2017). RDF supports it as external APIs.

4. Data collection

Data are essential components that provide complete detail about a specific instance. In the blockchain-based agriculture value chain ecosystem, data are collected from different silos and processes. In precision farming, agriculture data and information flow comprise four stages: planning, application, result, and evaluation. These stages contribute to data collection and analysis for real-time decision-making (Xiong et al., 2020). For data collection, e-agriculture is divided into two phases: (1) the pre-harvesting cycle that includes inputs and credit supply, and (2) the post-harvesting cycle consists of the marketing and product supply to consumers. The blockchain IoT-enabled agriculture data and their collection processes are discussed in this section.

- *Environmental data*: Collecting real-time data from IoT devices such as water sensors, soil sensors, Global Positioning System enabled weather data that plays a vital role in the quality of the e-agriculture product that is to be grown.
- *Production Data*: Data emanating from different stakeholders from e farming system, including farmer, distributor, warehouse, logistics, retailer, and consumers, add traceability in the value chain by providing transparent movement of agriculture products between different stakeholders (Yu et al., 2017).
- *Administrative data*: Using land registry and farm population data, the government can directly link subsidy schemes or financial aids to the farmers' accounts. It also covers crop insurance, fertilizer subsidy, and farm infrastructure support schemes.
- *External agency/supply chain data*: Any other external agency like e-commerce delivery platform, modern retail store and export houses can link to the value chain for additional capabilities and competitive advantage to farm produce.

Table 1
Stage-wise description, risks or costs involved, and benefit of the integration.

Stages	Description	Costs/risks involved	Potential benefits
Data Collection	Data collected from different agri-based IoT devices using APIs and standard data interfaces that deliver real-time information.	In the case of large-agriculture land, many such IoT devices are required to set up to establish costs. Also, to transmit real-time data to blockchain requires good (power) connectivity.	Farmers, who are owners of the farmland can monitor their land parameters from distant locations, resulting in costs saving on on-field labour.
Data Validation	Data Collected from agri-based IoT devices are validated using consensus algorithm and hash function. Also, artificial intelligence and machine learning libraries can be used to manipulate data.	Consensus such as PoS, PoW consumes lots of energy and processing power as each node validates and processes the transaction.	RAFT consensus in private blockchain helps in fault tolerance and increases the throughput rate of transaction and requests from the multiple agri-based IoT devices.
Data Security and Privacy	Digital data/information generated on the-agriculture system is susceptible to quality, crop production, and livestock production.	Implementing data security consumes additional computational resources and energy.	To develop trust between farmers and other value chain actors needs digital data that is fetched from secured IoT devices. Blockchain identifies a correct public or private key, crypto-graphical algorithm, SHA decryption, and encryption algorithm. Farmers and farm-related data collected, manipulated, and validated remains secured within the blockchain.
Data Storage	Agri-based IoT devices fetched data are to be stored in the blockchain that becomes easier to access and share with an authorized key. Crypto-graphical blockchain nodes in the form of a graph database can store the collected data.	Data storage in blockchain requires additional hardware nodes in the peer-to-peer (P2P) network in the distributed environment.	Storing e-agriculture data in blockchain in the crypto-graphical format in a P2P network increases the traceability of agri-products at any given point in time.
Data Sharing or Data Transmission	Blockchain technology helps to securely share data with external agencies and authorized stakeholders participating in the agricultural value chains.	This requires generating the individual private key for each participant.	e-agriculture data involves many stakeholders. Data sharing using the FAIR principles help create a complete set of blockchain data findable, accessible, interoperable, and reusable.

Source: Authors' inputs and compiled from literature.

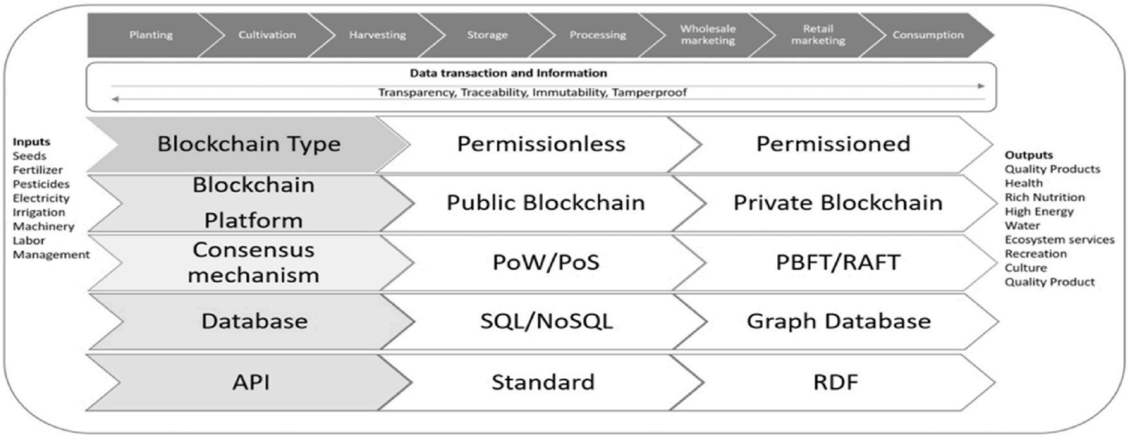


Fig. 2. Blockchain-enabled data and information flow in agri-value chains.

Table 2
Blockchain typology and characteristics.

Blockchain architecture options	Permissionless	Permission
Public	• Anyone can join, read, write, or commit • Hosted on public servers • Anonymous, highly resilient • Low scalability • Limited transaction throughput with high latency • Due to design, nearly impossible to tamper with transactions • Fully decentralized	• Anyone can join and read • Only authorized and known participants can write and commit • Medium scalability and limited scope leading to higher efficiency • Dependent on design, in general, transactions more easily tamper • Partially centralized
Private	• Only authorized persons can read and write • Hosted on private servers • High scalability • Limited transaction throughout • Partially centralized	• Only authorized persons can join, and read, • The network operator can write and commit • Very high scalability and limited scope leading to higher efficiency • Dependent on design, in general, transactions have more easily tampered • Fully centralized

Source: Adopted from Niti Aayog (2020) Blockchain - The India Strategy Part I, Pahl et al. (2018).

4.1. Environmental and production data

4.1.1. Soil health data

Soil is a significant source of several nutrients needed by crops for growth. The three primary nutrients are nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O). Nutrients are available in soil influence the type and quality of agri-products. So, soil testing and issuance of soil health cards have been essential to defining soil quality, structure, and texture in farmland. Real-time soil data can be linked to the blockchain ecosystem, and that data can further be connected to the virtual soil health card of that land with a specific latitude and longitude. It exhibits real-time soil health, measuring moisture level, type of fertilizer and pesticides used by farmers, aeration, etc.

Blockchain smart function fetches data from IoT sensors installed on the farmland, pre-defines the data logic process, and uploads IoT data into the blockchain ecosystem, as shown in Fig. 3. Data logic validates the information as passed by IoT sensor devices and stored in the blockchain. IoT devices can monitor and certify soil quality, surface, and sub-surface water quality, weather data, and real-time store data in blockchain that helps create data transparency and real-time instance of the farm and agri-products grown linked with a unique cryptographic hash key.

4.1.2. Seed quality tracing

Quality seed is defined as varietal pure with high germination or viability percentage, which is devoid of disease and organisms, and proper moisture content and weight. Quality seed ensures good germination, rapid emergence, and vigorous growth. One such factor affecting seed quality can be the viability of seeds sown. As blockchain integrated IoT for e-agriculture helps to trace and track the seed supply chain, namely breeder and production units that supply quality seeds and examine whether a proper standard is maintained at every stage of seed production (refer to Fig. 4).

4.1.3. Fertilizers and pesticides supply chain tracing

Fertilizers and pesticides are critical inputs that need to be tracked in their production and distribution. Fertilizers such as ammonium nitrate and pesticides, namely insecticides, herbicides, and fungicides, are explosive. If proper transparency and tracing are not performed, these may go to unscrupulous actors for wrongdoings. Therefore, end-to-end traceability is vital for the fertilizers and pesticides value chain. To grow a quality product, it is essential to use the right dosage of fertilizers and pesticides. If the farmers plan to produce organic products, they need to follow specific criteria and use organic fertilizers and pesticides. Blockchain keeps the record of what types, ingredients, and dosage of fertilizers and pesticides are used in the crops.

4.2. Administrative data

4.2.1. Farmers' subsidy

The government provides a subsidy for agriculture inputs and credit to farmers to strengthen infrastructure support and reduce their cultivation costs. The current system has failed to provide transparent and real-time data of farmers who require such subsidies. The central government is dependent on the states or such verifying agencies that offer a list of farmers for distributing subsidy. A blockchain ecosystem is being established that integrates and interoperates different e-Governance (Government to Citizen or G2C) existing databases from where smart logic can fetch farmer data needing subsidy as per the predefined functions. For example, farmers buy nitrogenous fertilizers (Urea) at a subsidized rate. In this case, the smart process can validate farmers' data on whether they are eligible for a subsidy or not and link them with the state or central government's subsidy scheme.

4.2.2. Financial aids to affected farmers

Farmers often avail credit from financial institutions for farming in the form of crop loan or Kisan Credit Card. At the time of natural calamities like floods, drought, there is a high likelihood of crop damage

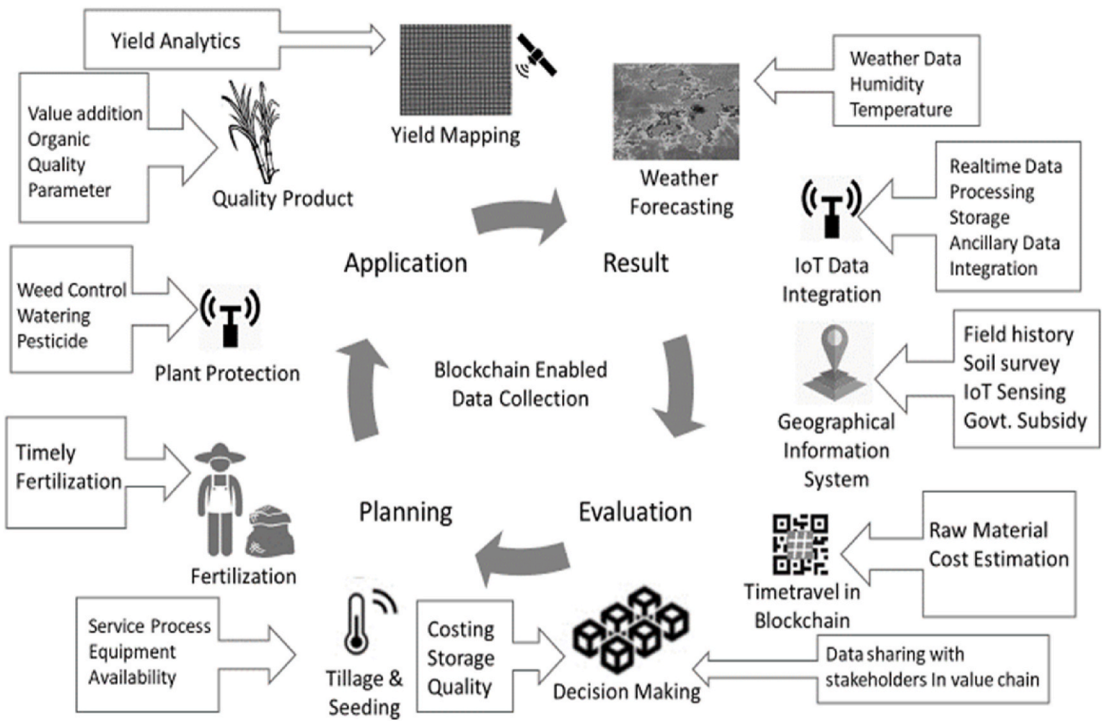


Fig. 3. Blockchain integrated ICTs application in e-agriculture data and information flow.

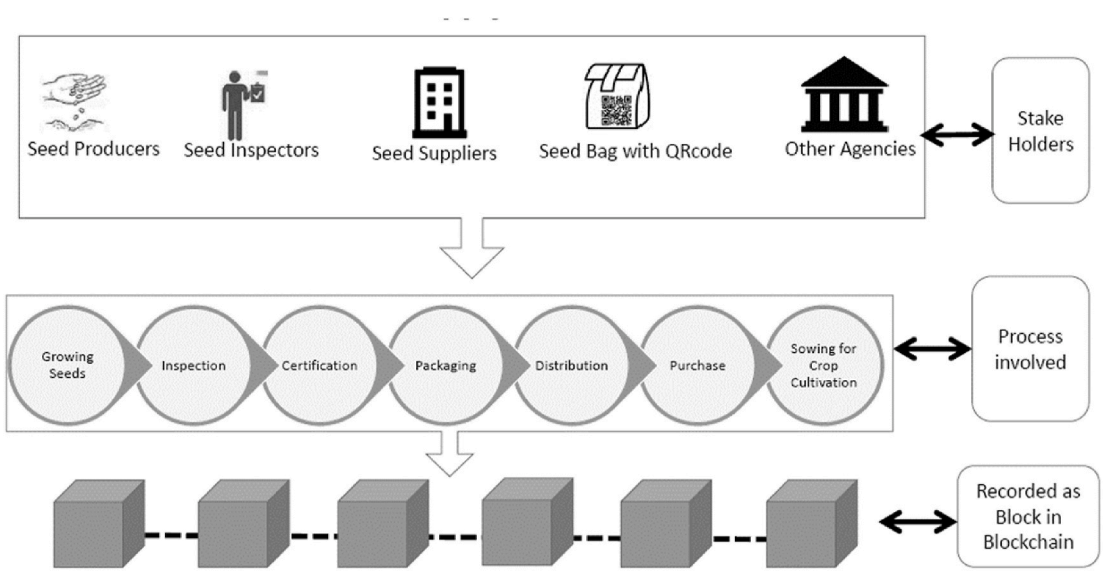


Fig. 4. Blockchain-enabled seed quality tracking and tracing.

and farmers' income loss. In such a scenario, farmers would be in extreme need of financial aids to repay their loans. The current system takes several months to identify the beneficiary. As a result, farmers do not have other options and eventually, commit suicide. Under this circumstance, the blockchain eco-system can fetch data from Geographical Information System integrated weather system and link these data with the land record registry database. Linked data can be validated through a smart function to identify severely affected areas and least affected areas. Required data can be fetched with complete details of farmers, land, and accounts linked to farmer identity cards such as Aadhaar-based Biometric Authentication (for India). It is proposed that an interoperable system can fetch and provide farmers' real-time data and transfer financial support to the authorized accounts via direct benefit transfer.

4.2.3. Land registry data

The land is an immovable property, and to prove the ownership, one should provide a legal document that should conclusively support it. One is presumed to be the owner until proven otherwise. Moreover, various departments maintain different records, creating data duplication that is easy to modify or tamper, and anyone could use to stake a claim on the land. This leads to numerous disputes, and farmers often face problems to claim in their records of rights in the land registry department. Collecting land registry data in the blockchain can make it immutable to help farmers' authenticity of their farmlands. The land registry data can also be used to link it with a direct government benefit transfer scheme and aid transfer due to natural calamities by integrating it with the geospatial system (Sekhari et al., 2019).

4.3. Agriculture supply chain data

4.3.1. Traceability from farm to fork

There are two types of agriculture commodities or products in agriculture that moved along the supply or value chain: perishables and non-perishables. Perishable commodities such as fruits and vegetables have a shorter shelf-life than non-perishables such as cereals, pulses, and oilseeds that require concurrent optimization from harvesting until it reaches to plate. In contrast, non-perishable products are often subject to black marketing, as intermediaries store such products and sell when prices escalate. It is crucial to trace such a product at any given point in time. When one can aim to digitize the agri-value chain in agriculture, ensuring transparency at every level is necessary. When it reaches the consumers, they can be confident and develop trust in product quality and safety standards. In other words, blockchain technology can foster trust for farm products so that consumers can repose faith in such products. The mechanisms of how blockchain can improve traceability from farm to plate are illustrated below.

4.3.2. Distributed and decentralized records management

The agri-value chain consists of complex processes, and stakeholders need to be brought under a data channel in which all of them can transparently update the relevant information. A distributed ledger network of blockchain provides an integrated platform for the peer-to-peer nodes in the value chain where authorized participants can share and retrieve real-time data. Distributed nodes with blockchain can secure the system and help integrate where they create a single data pool.

4.3.3. Concurrent optimization

While developing a smart agriculture value-chain, it should account for backward integration and forward linkages, as shown in Appendix 1 (Figure A.1). So, existing resources can work concurrently for optimizing resource utilization and creating a system efficient and transparent. The blockchain system allows stakeholders to optimize components and resources critical to inventory management, staff allocation, and lead-time between each stakeholder. The optimization feature gives a complete insight into the product and actors, who may be accountable for interrupting or hold up supply chain processes (Dai et al., 2019*)*.

4.3.4. Demand synchronization

In the agri-value chain, demand the forecast depends on historical data and stochastic processes and one can further, increase the accuracy of forecast on consumers' buying capability. Decentralization of data is necessary for the supply/value chain process developed from the buyer's perspective and analysing that data on the blockchain can improve demand by reducing the forecast error (Viswanathan et al., 2007).

4.3.5. Tracking provenance

In e-agriculture infrastructure, blockchain can interface with IoT sensors, namely soil sensors, water, Radio Frequency Identification (RFID) tags, digital manufacturing equipment, drones, GPS tracking, intelligent devices, and other write-enabled technologies to provide a real-time transaction value called token (Lin et al., 2018). Data can further be used for an efficient production schedule, food safety, and anti-counterfeit efforts. Consumers often demand organic food for health safety, and they should know what processes are followed in production. Blockchain helps track a complete chain that can record whether quality parameters are blended appropriately to maintain food safety and product standards.

5. Data validation

5.1. Blockchain consensus mechanism

e-Agriculture the system generates different types of data, as discussed in the earlier section, tagged to agricultural raw materials. These semi-finished or finished products travel along the various stages of agri-value chains. These data require faster validation to make the system robust. As compared to the commonly used public permissionless blockchain, permission blockchain and RAFT consensus algorithm can gain ground for verification and security (Wang et al., 2019b).

First, the system is highly efficient in preventing transactions and queries from bad actors by not allowing their votes to count in the consensus algorithm and restricting them from writing, reading, or committing transaction information.

Second, RAFT consensus on the consortium blockchain allows for the leader and follower role changes on a rolling basis to protect against unfound consensus members influenced as a leader, as shown in Fig. 5. In this system, transaction verification and validation can only be made through IoT devices that physically has membership in the consortium. With the RAFT consensus algorithm, the proposed blockchain platform becomes not only energy-efficient but faster and scalable that can record thousands of confirmed transactions per second across multiple ledgers (Huang et al., 2020).

Third, blockchain with the RAFT consensus mechanism provides a transparent, secure, and trusted platform for faster exchange of all types of services among stakeholders. The RAFT consensus mechanism guarantees integrity if more than 50% of transacting nodes are honest. The RAFT-backed blockchain database is highly scalable and can confirm thousands of service transactions within 1 s across multiple ledgers (McConaghy et al., 2016). Fourthly, agri-IoT devices relate to the network by issuing transactions and querying the blockchain for the required data. In this case, permission blockchains are inherently faster, scalable, and provide more transaction privacy. Compared to the Proof of Work or Proof of Stake consensus mechanism followed in permissionless blockchain, the RAFT consensus mechanism reduces transaction costs and energy consumption verifying transactions and improves scalability (Wang et al., 2019b). This achieves fault-tolerant, attack-resistant, and collusion-resistant transactions. The consensus leader can be elected and verified continuously as a valid actor in the RAFT consensus mechanism. The network can be monitored (via interval-controllable heartbeat) to operate when the members are inaccessible. All eligible members of the panel can create blocks to record transactions and prevent non-trusted parties from participation. Thus, it is impossible or disadvantageous for anyone to cheat under RAFT consensus algorithm rules.

Several agri-based IoT devices are embedded into blockchain. Thus, a consensus algorithm for the distributed architecture helps establish coordination between the multiple IoT devices. An agreement can be set out for the various nodes, for example, agriculture wireless sensors, pond fish sensors, and other IoT devices. For arriving at a consensus between the multiple action nodes, several consensus algorithms have been proposed, namely PoW, PoS, (Practical) Byzantine Fault Tolerance (P)BFT), and RAFT. PoW and PoS are mostly used in the public blockchain, but they lack the speed of transaction confirmation. As a result, this consensus algorithm reduces the usage of connecting an array of agri-based IoT devices with blockchain. In contrast, the RAFT consensus algorithm has higher efficiency and is easier to use in private blockchain (Huang et al., 2020).

5.2. Time travel study

As data authenticity at the field level is critical, blockchain ledger needs to be linked with the graph database. This relationship is depicted in Fig. 6 that allows for all block member transactions entered in the ledger for co-existence in the relationship-rich graph database. An

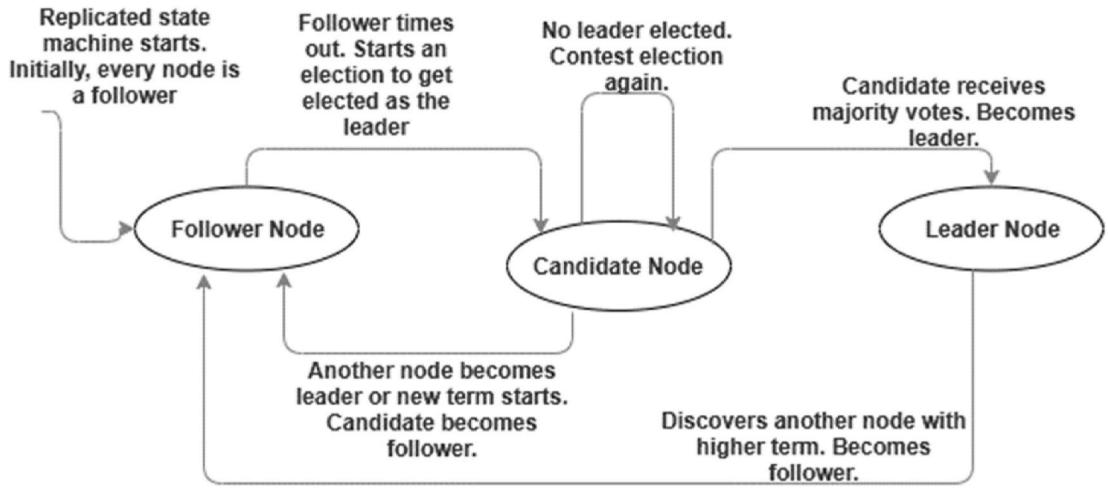
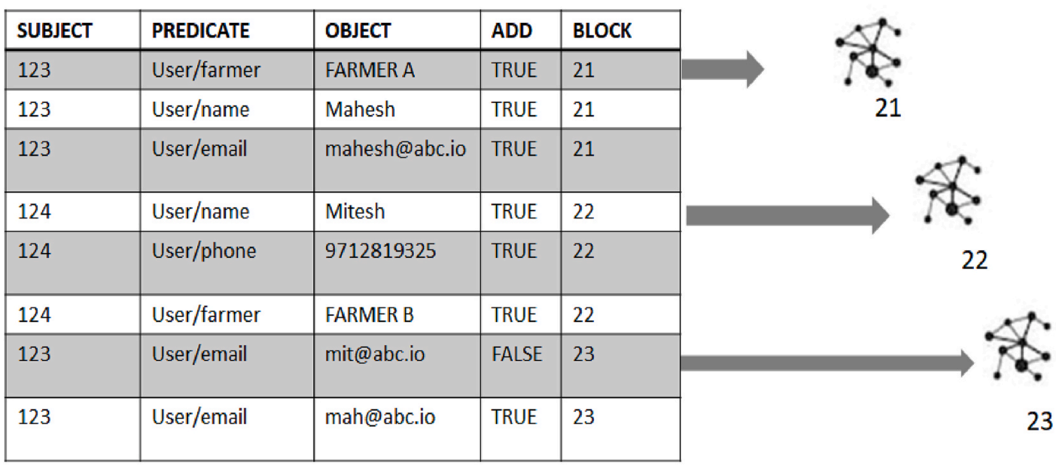


Fig. 5. Leader-follower structure of RAFT consensus mechanism.



SUBJECT	PREDICATE	OBJECT	ADD	BLOCK
123	User/farmer	FARMER A	TRUE	21
123	User/name	Mahesh	TRUE	21
123	User/email	mahesh@abc.io	TRUE	21
124	User/name	Mitesh	TRUE	22
124	User/phone	9712819325	TRUE	22
124	User/farmer	FARMER B	TRUE	22
123	User/email	mit@abc.io	FALSE	23
123	User/email	mah@abc.io	TRUE	23

Fig. 6. Blockchain ledger and graph database integration.

illustration of consumers' product purchase considering the time travel study of blockchain is described below.

5.2.1. *Consumers' product purchase*

When consumers receive agri-products, they can verify the authenticity of such products. For example, if an organic product is delivered, it can be verified through the blockchain ecosystem that further fosters trust among buyers about the product's quality. Buyers can trace through time travel study and check the temperature, moisture level, quality specifications while transporting, the grower's name, the frequency of spray of pesticides and fertilizers used, seed quality, soil quality, etc. An illustration through Fig. 7 shows the product's time travel from the grower's field to the consumer's plate. While providing the consumers with blockchain-based solutions, authentication or

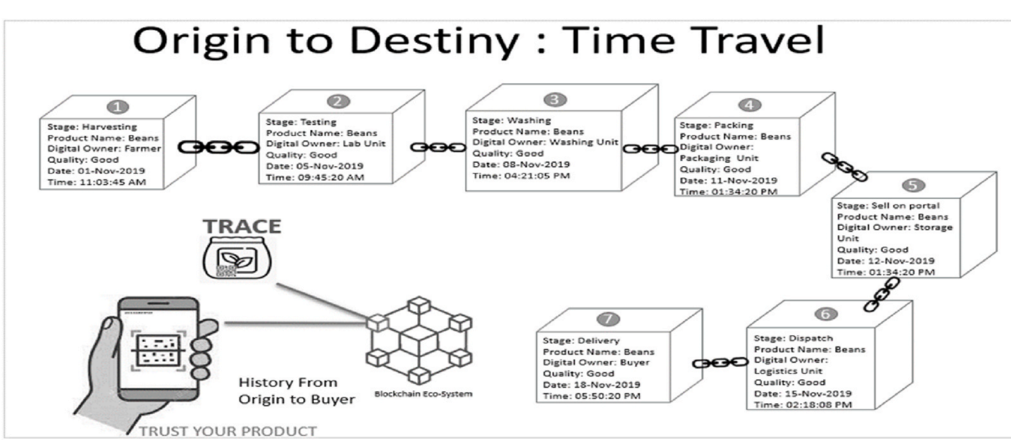


Fig. 7. A pictorial presentation of blockchain-enabled time travel study.

validation of the agri-products is essential by improving the electronic traceability system. The data security principle plays a pivotal role in the authentication of the product.

As new transaction entries are made, falsification of existing data can be performed, and the original transaction payload is appended to the graph database. Data are added to the ledger and database in blocks #21, and #22 is added to the graph. In contrast, in block #23, both a new fact is added (an email update in this case), and the falsification of a previous fact (the old email address) is appended. With each transactional block-addition, the graph's growth with the relationships can remain in-tact (Dubey et al., 2015). This allows for a near-instantaneous query capability by crawling the relationships of all elements in the graph. The query capability makes it possible to ascertain database state for all current and historical data at all 'action' nodes and provides a method to forecast the future by reviewing the historical dataset. This functionality, referred to as 'time travel' significantly increases transaction speed and accuracy of historical transaction records.

5.3. Blockchain smart contract logic

Agri-IoT sensor devices generate multiple types of real-time data. Smart, functional logic is defined when real-time data enters the blockchain for validation. The smart, functional logic can further be upgraded by linking Artificial Intelligence and Machine Learning libraries that intelligently update by learning the real-time data patterns and comparing them with the past historical data (Nassar et al., 2020).

Smart functions can be tailored to set permissions and delimit unwanted functionality without requiring application-layer approval. Since smart functions secure data at the source, these can be updated quickly to reflect the current state of sources. For example, when data are shared between diverse agri-value chain actors, the smart function can restrict access to the dataset for a specific stakeholder to update data and query data by other entities (Bhamidipati et al., 2019). In this case, if 'IP spoofing' is being detected, the smart function can temporarily be updated to exclude that IP to improve data security. Further, blockchain includes multiple layers of write transaction validations to ensure that a valid actor follows transaction related processes, namely (1) data added to the ledger from a particular stage of the supply or value chain; (2) the transaction follows the appropriate formatting for the database schema, and (3) all rules at the data-layer for permissions and business logic need to comply with smart functions (Kshetri, 2017). Fig. 8 depicts the-transaction-writing-the-validation process.

5.4. Atomicity, consistency, isolation, durability

A blockchain-enabled distributed database follows a consensus mechanism for a joint agreement on the network parties' data block. The blockchain database supports complex data types, rich query structure, ACID compliant, low latency, fast scalability, and distributed architecture. The inclusion of the database features can leverage the blockchain with low latency, high throughput, rapid scalability, and complex data access queries. So, the application enhances its efficiency and security (Raikwar et al., 2020).

6. Data security, storage, and privacy

Data are often available in many different locations and replicating data into various data lakes must build a standard set of information for analysis and data sharing. With this replication level, data security is not comprehensively controlled, as it is derived from application front-end and middle-tier security logic. The use of APIs and the development of data lakes represent cost, inefficiency, and redundancy of data and create 'yet another attack surface' to data exposure. It is a direct pathway for hackers, and some essential data has been breached in recent years.

First, the improvised solution to secure data transportability is to "defend data itself" at the data layer–a core concept of the data-centric architecture approach. In this approach, the permission for access and modification of data are stored as codified data elements. When data are accessed or moved to another location, the inherent permissions are carried along with the root data. Data-centric security can be a better solution for shared datasets openly accessible by stakeholders, each with a varying degree of access permission. These rules govern data protection and can be used to enforce schema rules for consistent data governance (Shrier et al., 2016).

Second, public, and private key cryptography and data-centric security are combined to provide a robust data security foundation. When dealing with a distributed or decentralized environment, a data-centric approach to information security is critical to data-scaling for multiple stakeholders. Various stakeholders need to transact and query against a decentralized database. Standards like W3C RDF assume an important role, and RDF formatting empowers data to be accessed across disparate data sources, combined, and leveraged. With data-centric security and blockchain proof and trust, RDF standards can expose the interoperable datasets for applications. Data security is a pre-requisite for interoperability. If one wants to democratize information access across the actors,

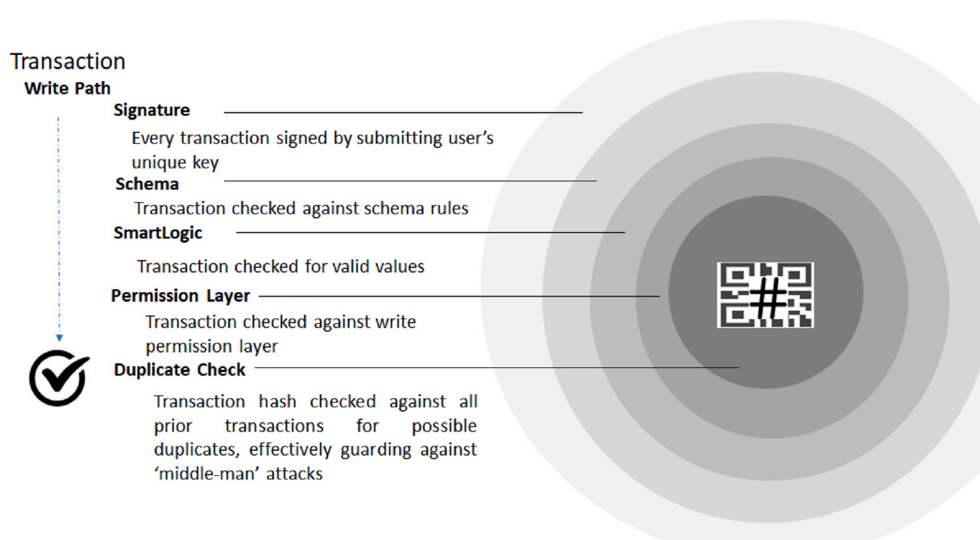


Fig. 8. Transaction write validation.

one should need to devise a scalable model for securing data at its source (Brickley et al., 1999). Next-generation data ecosystems like digital assistants and web 3.0 technologies would be required for scalability to secure interoperability.

It is important to note that blockchain provides data security and privacy using SHA256 encryption. Tamper-proof data can be stored and secured either in SQL/NoSQL database (for permissionless public blockchain) or in a graph database (for permission private blockchain).

Security keys include the following.

1) Hash Function for data security: To insert a combination of data into the block, the hash key of the previous block and a random digit called "nonce" are combined to form a hexadecimal hash ID for that block. The next block can use the hash ID of the last hash ID to create a complete chain of blocks.
2) SHA Encryption: A layer of security is added using SHA Encryption whenever data are stored in the blockchain, followed by proper validation (Fakhri and Mutijarsa, 2018).

6.1. Data storage

Blockchain technology collects data from different sources, including farm sensors, agri-based IoT devices, Geographic Information Systems, UAV mapping services. These data can securely be stored in blockchain when an agri-product travels through the value chain where various stakeholders are associated. They update different data streams into the blockchain, including GPS data and temperature data defining products' quality. When the product reaches the buyers, they want to know whether this product attains specified quality standards, which translates to trust in fostering the trade. This can only be maintained if all the data are accessed at each point of time and are securely stored and tamper-proof. Besides the cryptography and hash function, Merkle Tree, nodes, smart contracts are critical to data storage and record management.

- Merkle-Tree forms a structure used in BitTorrent, Git, Bitcoin, Ethereum, and Hyperledger that summarises data of all related transactions in a block by producing a digital fingerprint in the form of a hash called transaction ID for each transaction and every pair of transactions after that until only one unique ID, or hash is left. The Merkle Tree records transactions in chronological order and verifies whether the record has been altered or tampered with or whether the record has been branched or forked (Niti Aayog, 2020, p. 54; Saurabh and Dey, 2021).
- Action nodes maintain a copy of the most updated state of the blockchain distributed database and participate in the authentication of new changes. However, all nodes may not store a full copy of a blockchain or validate transactions (Niti Aayog, 2020, p. 54).
- Smart contract represents an if-else construct that enables blockchain-based systems to autonomously record a transaction if specific pre-requisites are completed (Niti Aayog, 2020, p. 54).

Fig. 9 presents the agri-IoT based Distributed Ledger Technology for data storage below. A comparison of selected DLTs is important for consideration to use in e-agriculture. As a high degree of trust is to be placed on blockchain developers and managers to manage the agency problem, the consideration of DLTs is critical to service providers involved in agri-value chains. A comparison of various DLTs is reported in Appendix 2 (Table A.1).

6.2. Data privacy

It is recommended using the public key and private key for identity authentication in multi-factor authentication for data privacy. A request about the specific information/data can be shared with those users who have access permission. Also, facial recognition, iris recognition, biometric thumb impression, and a combination of passcode or pattern can be used to authenticate the identity (Rathgeb and Uhl, 2011). Blockchain affiliated Distributed Ledger Technology (DLT) consists of private and public keys. e-agriculture stakeholders who participate in permission blockchain can access data as per the key and access role designated to that specific activity as defined in the smart contract. Activities of each participant accessing data from the blockchain can also be logged into the *audit trail* with a timestamp to maintain data privacy. The smart agri-IoT devices generate data such as water composition, temperature, humidity collected in real-time. These provide accurate data about the farm and the environment. Farmers can make an informed decision based on the values obtained by this sensor. For example, if the soil pH increases, farmers can reduce the ammonia supply to the soil. But if the data are not secured, it can induce physical attacks by disrupting soil or water pH setting. Personalized privacy can be adopted in IoT-based

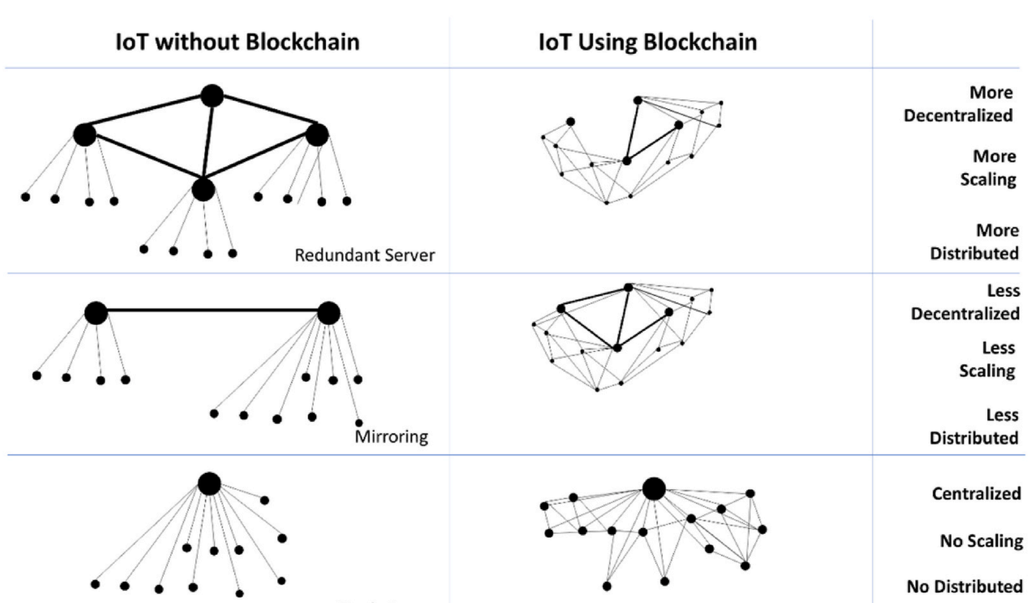


Fig. 9. Agri-IoT based Distributed Ledger Technology for data storage.

agriculture devices connected to the blockchain (Li et al., 2020). A searchable encryption scheme, as mentioned in Ferrag et al. (2020) research work, can be adopted for the data privacy of agri-IoT-based blockchain systems.

7. Data sharing

7.1. FAIR principles

e-Agriculture involves continuous or staggered data generation and collection via various sensor devices or IoT. Therefore, it requires the blockchain-based solution to store data so that it would be easier to find and access it from any other system. In other words, it should be interoperable with the existing e-agriculture system and easy to reuse data stored in blockchain by replacing different silos of data (Wilkinson et al., 2016). FAIR guiding principles embrace the deep-rooted notion of data-centricity. Data is a core asset that should be treated as versatile, reusable, and valuable, a reproducible resource for analysis or downstream applications (refer to Fig. 10).

FAIR principles provide digital information with the characteristics that need to be found, accessed, interoperable, and reused by communities after the publication of initial data (Wilkinson et al., 2016). The guiding principles allow data and metadata to generate insights for various stakeholders by evolving into a dynamic set of shared knowledge. It helps realize data's recyclable value, injecting context into data for enterprise knowledge, powering machine-to-machine autonomy for e-agriculture, making data artificial intelligence-ready, and empowering democratic ownership. FAIRness promotes semantic data context, which is a critical ingredient in enterprise knowledge graphs. Semantic standards allow for a universally shared understanding of data format for instant interoperability.

7.1.1. Findability

Findability is an essential minimum requirement for good data management but can often be overlooked when dealing with agricultural products. Electronic agriculture data, human beings and machines should be able to find it. It comes down to utilizing rich, schematically prescribed metadata to describe the information to augment consumers' decision-making.

7.1.2. Accessibility

Once agri-data is found in blockchain, it should be accessible to various stakeholders at the protocol layer with predefined data access controls. Data uses a standard communication protocol, and it should be retrieved without proprietary protocols that make data available to a broader range of systems. Data ownership, permission, and control should be integrated into FAIR data principles because data are technically accessible to diverse stakeholders or value chain actors via an open protocol. So, one needs to ensure a scalable identity and access management system.

7.1.3. Interoperability

In e-agriculture, data are generated from the different systems which are accustomed to other protocols. It is considered that blockchain technology embraces a system that can accept any system running of any protocol converting each silo of data interoperable. RESTful Web services and APIs provide interoperability between computer systems on the internet. RESTful Web services allow the requesting systems to access and manipulate Web resources' textual representations by using a uniform and predefined set of stateless operations (Rodriguez, 2008).

7.1.4. Reusability

Agri-data consists of multiple stakeholders. Front-end applications and agri-IoT sensors devices such as GPS tracking during transportation, soil condition, and water quality data and digital machines generate data with a varying degree of layered collaboration with minimal human intervention required. So, FAIR data principles should be implemented to extend data utility in e-agriculture value chain and provide a source of trust to value chain actors.

8. Blockchain–IoT architecture

Based on the above discussion, a blockchain integrated IoT architecture is proposed that consists of a presentation layer, business layer, functional layer, integration layer, and blockchain data layer (Hassan et al., 2020). The architecture design can improve the existing IoT-based architecture (Chen et al., 2017) for the information system scalability, flexibility, and resilience, as shown in Fig. 11. In most of the literature, three to four layers are proposed: device or IoT layer, core network layer, application layer, and user layer. This architecture is built on existing state-of-the-art technology with integrated and specialized technology solutions for sustainable e-agriculture. The proposed architecture for e-agriculture information systems define components and segregate activities at various layers to create the integration of information systems and databases in the business layer, data processing in the functional layer, storage, and security of data in the blockchain data layer, displaying the information through the presentation layer.

1) Presentation layer

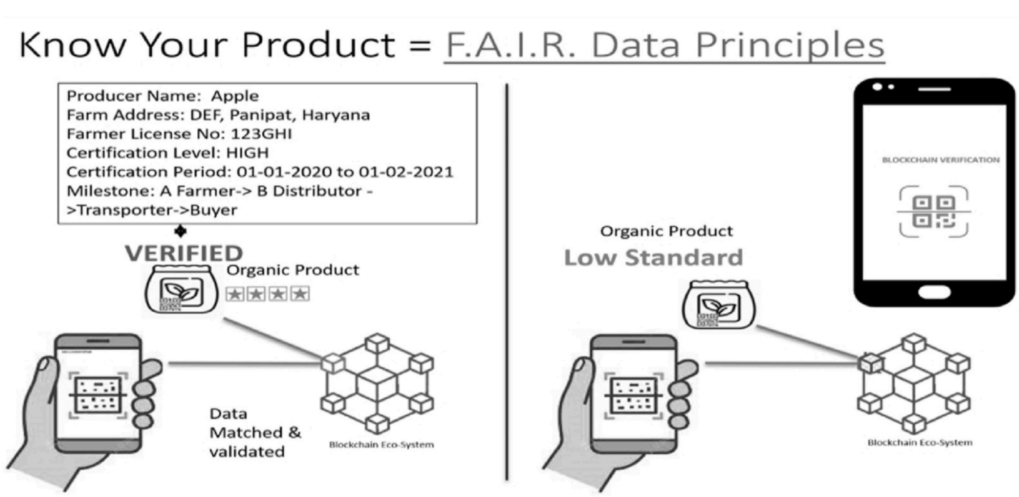


Fig. 10. Application of FAIR principles in product authentication.

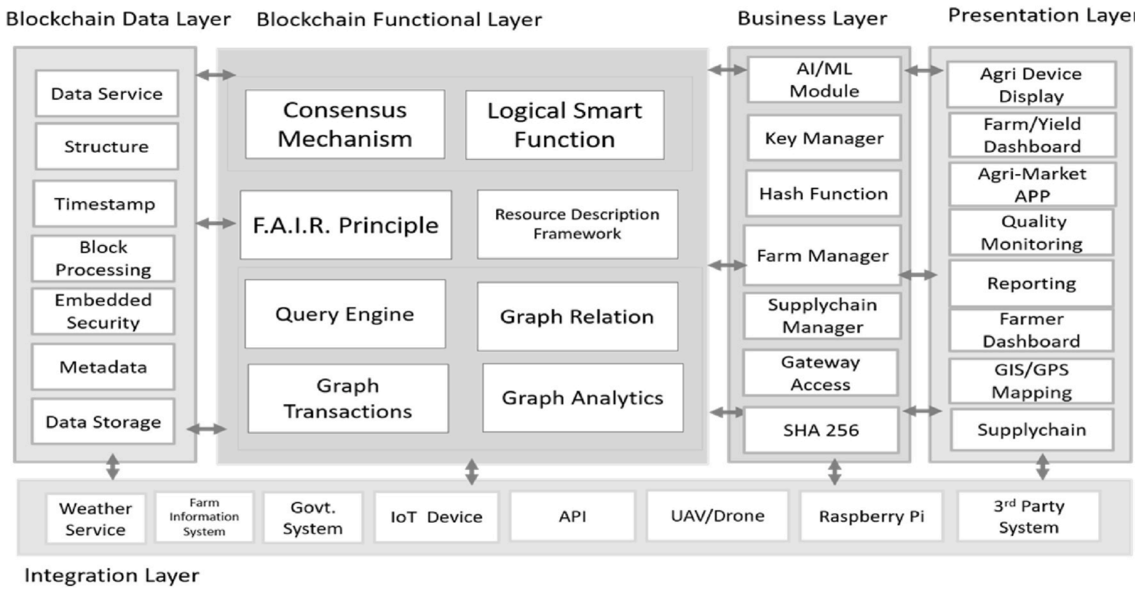


Fig. 11. Blockchain- IoT architecture for sustainable e-agriculture.

Front-end graphical user interface is the presentation layer. Agri-based IoT-devices work on different logics and operating systems. Therefore, one can design a blockchain solution in such a way that it becomes language independent. The presentation layer provides a generic view of all modules that are integrated and manipulated to achieve the desired result, including IoT agri-devices, field/farm monitors, soil and water monitors, data analysis using satellite imagery, gridded land maps using GIS/GPS can be presented and displayed on this layer. All events of agri-food supply chains, as well as e agri-market, are available at this layer.

2) *Business layer*

The concept of the public and private keys can be used in this layer using a key management module to authenticate front-end devices. Cryptographic hash functions can interact with the presentation layer as per the hash key being generated. The business layer can handle all the management parts. Predefined libraries that work on agri-based artificial intelligence and machine learning can be embedded in the business layer.

3) *Functional layer*

The fault tolerance mechanism defined in each node is proposed to run through the functional layer. The smart function can help run code to validate a process or transaction passed by the business layer. It is also defined in FAIR data principles to manipulate the request generated. Query language processing takes place through the Resource Description Framework that can increase the speed of executing a query or transaction using a graph database model.

4) *Integration layer*

For a blockchain ecosystem in e-agriculture, it is necessary to define a system that can backward and forward integration. This can make the entire system interoperable, semantic and can integrate smart devices or agri-IoT sensor devices. Services for external systems such as weather-related services, crop and livestock advisory services, land record registry systems, e-governance, the supply chain can be integrated into this layer.

5) *Blockchain data layer*

A convivial ecosystem is necessary to defend e agricultural data, and blockchain offers improvisation in data security and privacy through built-in threat models (Ferrag et al., 2020). Data collection, data validation, and data processing occur in this layer. Metadata created through a graph database can securely be stored in a blockchain that brings in data privacy.

9. Discussion and conclusions

This study proposed a sequential yet integrated applications for data collection, data validation, data security, data storage, data transmission in e-agriculture by integrating blockchain technology and IoT network. As the integration of blockchain technology and IoT ensured data rights and defended data duplication problems, this paper devised a hybrid platform to create an interoperable, decentralized, scalable, and fault-tolerant e-agriculture information system and potentially contributed to prior research (Chen et al., 2017, 2020; Linsner et al., 2019; Torky and Hassanein, 2020).

This study explored two research questions. One was how the integration of blockchain technology and IoT could improve data collection, data validation, and data management in e-agriculture. To address this question, the study presented agriculture data into four categories: environmental data, administrative data, production data, supply chain/external agency data. For each type, this study described data collection processes and designed the way backward and forward integration in e-agriculture information systems are established the technology coupling (Xiong et al., 2020). Apparently, in e-agriculture, data collection is a tedious job that concerns data curation and authentication. For example, crops or weather insurance data need to be collected through IoT network and stored in blockchain DLTs for distributing financial aids to the insured farmers' accounts and strengthening commodity risk management (Sylvester, 2018). Also, fertilizers subsidy, seed distribution, price support scheme coverage to farmers requires farmers' identity proof, landholding records, crop and livestock details, and so on for data authentication and validation that can be achieved through the proposed blockchain-IoT architecture. In this regard, various illustrations in different stages of data management were presented to help agriculture value chain actors appreciate the nuances of blockchain IoT-based e-agriculture information systems. On the one hand, the blockchain consensus mechanism plays a vital role in data validation for data storage in the distributed database (Wang et al., 2019b), this study, on the other, proposed that permission blockchain could restore sensitive data for government/regulatory authority to improve real-time decision-making and service integrity (Walport, 2016). Blockchain-enabled time travel study for supply chain traceability and transaction-writing-the-validation are integral to data provenance and authentication (Huang et al., 2020; Kamble et al., 2020). Data sharing using FAIR principles help create a complete set of blockchain data findable, accessible, interoperable, and reusable (Wilkinson et al., 2016). FAIR guiding principles add to blockchain-data security and privacy (Kshetri, 2017; Ferrag et al., 2020; Pahl et al., 2018; Walter et al., 2017). Since scalability appears a major concern for blockchain users, this study proposed to append Artificial Intelligence and Machine Learning (AI-ML) modules in the RAFT consensus-based a layered blockchain IoT architecture (Huang et al., 2020). Data-centric rules govern data protection and can be used to enforce schema rules for consistent data governance in e-agriculture (Shrier et al., 2016).

The second question raised was how blockchain integrated IoT architecture can enhance capabilities and strengthens agri-value chain actors' decision-making to transform conventional agriculture into a smart farming system. The study revealed that input suppliers could register in the blockchain ecosystem to supply certified seeds, fertilizers, and irrigation equipment. Their data can be shared with government agencies for identity checks and verification using smart contract logic (Ali et al., 2018; Nassar et al., 2020). The elimination of intermediation in the supply chain would reduce transaction costs and lead time for product delivery at the farm gate. Secondly, farmers can strengthen their crop-choice decision based on soil quality and availability of inputs and can optimize their return-on-investment. After registration on the blockchain platform, individual farmers or their organizations can showcase online sales products. Farmer organizations can quote the price, selling quantities, available stocks or inventories, delivery charges, and upload their products' images. Also, they can edit their existing products listed on the portal and realize payments based on QR code of their products. Thirdly, food processing companies and micro-food entrepreneurs can reduce their risks and uncertainty of contract arrangements with food entrepreneurs and growers. The integration of blockchain and IoT can convert the value of agri-commodities procured from the contracted growers into digital information assets through tokenization, foster trust in the transaction, and improve contracts' governance and management (Lin et al., 2018; González-Zamar et al., 2020). Fourthly, buyers can moderate their purchase decision or reduce their post-purchase dissonance by viewing agri-products available at the the-agriculture *e-bazaar* portal of the blockchain ecosystem equipped with order placement, order tracking, invoice details, etc. Fifthly, the transparent and authentic data can guide the regulatory authorities to enter a tri-partite agreement with the contracting firms and farmers and improve the contract's governance and management. Sixthly, the knowledge repository section of the e-commerce platform embedded in the blockchain ecosystem can include case studies, participatory videos of value chain actors, and certified farming practices to promote sustainable e-agriculture. The integration of blockchain and IoT can optimize agriculturally chemicals' use to reduce greenhouse gas emissions and improve resource use efficiencies such as irrigation water scheduling and continuous monitoring of soil health, say pH, soil texture, proportions of macro and micronutrients, and chelating agents, etc. The blockchain-IoT coupling is necessary to analyse the growth cycle of crops, livestock, fisheries, and enhance agricultural productivity and quality of products complying with certification standards (Walter et al., 2017). To achieve sustainability goals, this study highlights the need for designing effective modalities for inclusive participation of diverse actors in the proposed architecture and underscores the importance of layer-based architecture to achieve techno-economic and environmental dimensions of sustainability.

To sum up, with the improvisation in data collection, blockchain can provide data privacy solutions through blockchain-based deep learning, distributed key management, access control, reputation and trust, authentication and identification and secure Software-Define Networking (SDN) solutions in e-agriculture. The proposed blockchain-IoT architecture would be empirically validated in future research. The research agenda would assess adoption intention processes for platform developers and users of e-agriculture information systems. The willingness-to-pay for adoption of the digital platform would be part of future research to decide the likelihood of rollout or scaling up of layered architecture in e-agriculture.

10. Implications

10.1. Theoretical implications

The present study makes a few important theoretical implications for scholars. First, the study lends insights into usage of blockchain-enabled distributed ledger technology (DLT) and IoT devices by diverse stakeholders to attain decentralization in e-agriculture information systems. As transcending towards agriculture 4.0 and green technologies are inevitable, smart contract enabled financial transaction, agri-based IoT devices, GPS, GIS, Mapping Tool, drone imageries, smart agriculture equipment and wireless sensor (actuator) networks are critical for information processing and mitigating information asymmetry, moral hazard, and adverse selection for value chain actors and regulatory authorities or government agencies. This will also reduce the inability of agriculture markets to internalize the externality benefits and social costs into the production, distribution, and consumption system. Second, for data management, the trusted and secured DLT is critical to decentralized agriculture information processing systems that are relevant to networking and can improvise real-time decision-making of value chain actors to capture gains in every possible node of the chain and make equitable value appropriation and value circulation in local or regional food economies and can integrate regional agri-food networks into Global Value Chains. Third, the proposed blockchain-IoT architecture presents a hybrid digital platform structure considering a cloud-based SaaS to constitute a network of diverse value chain actors contributed by exchange and adaption processes. The hybrid platform can engender the scope for decentralized agri-ecosystem for renegotiation of contracts and their governance and management. In that the information spillover between the actors would be real-time, and the network diffusion of technology-coupling innovation, and information exchange between upstream and downstream actors would optimize resource use, sustain agricultural production, bring diversity in participation, and improve access to quality and hygienic food products. Fourth, the implementation of hybrid and cooperative digital platform integrating blockchain technology and IoT can allow agri-business focal firms, upstream and downstream actors, certification agencies, regulatory authorities to deal with increasing transparency in business processes, disintermediation in transactions, data control and protection, elaboration of transfer ownership through tokenization of (digital information) assets.

10.2. Implication for practitioners

The study makes some important implications for agri-tech professionals and agri-business companies. Because blockchain integrated IoT concerns for social, economic, and environmental dimensions of sustainability in agri-food value chains, this transforms the conventional transaction into a value-sharing mechanism through tokenization of assets, which can be the basic unit of value exchange for the actors. So, the value generated in such a food system can help farmer collectives earn tokens, trade, or spend tokens via a shared platform. While value generation and the external market relationship may dictate consumption in part, the production, and distribution of agricultural commodities/products can be coordinated for decentralized governance in regional agri-food chains. Agro-ICTs and blockchain start-ups should design a hybrid adaptive platform by addressing the heterogeneity and pitfalls of blockchain technology. Some anecdotal evidence can be drawn from European or Dutch economies where blockchain start-ups have created a shared platform for the producers and consumers (e.g., Fructus, Delicia), data infrastructure for traceability and food safety (e.g., Ambrosus, OriginTrial, and Te-Food), open networks for food co-operatives (e.g., Backfeed and Odyssey). Furthermore, start-ups in emerging markets have created blockchain platforms to improve smallholder incomes by connecting them with the local buyers (e.g., Agriledger, AgUnity, JivaBhumi, Agri10x, Agroplexi, Hara).

10.3. Implication for policymakers

The integration of blockchain and IoTs adoption can link the native producers with consumers by eliminating intermediaries and democratize the agri-food networks. This can create shared values and community wealth-owned and self-governed by its users, communities, and regional networks. Communal ownership and democratic governance as the central tenets of 'platform cooperativism' can prevent opportunist lead firms from plowing back surplus from the decentralized agri-food economies. A distributed blockchain ledger can promote decentralized e-governance in agri-food networks by improving coordination, control, and safeguarding of actor interests. Identification, and capacity building of food chain cooperatives and connecting them with the shared digital platform, however, requires a systematic and scalable techno-managerial intervention and renewed agriculture policymaking in the era of digitalization. Agri-food policy in developing and emerging economies can gradually institutionalize the interface of blockchain technology and e-agriculture information systems to ensure value creation, value appropriation, and sustainability of agri-food systems. With this policy prescription, the national government can design appropriate policies and regulatory architecture for blockchain technology-IoT-coupling adoption in agricultural and allied sector.

CRediT authorship contribution statement

Kushankur Dey: Conceptualization, Validation, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Investigation. **Umedsingh Shekhawat:** Methodology, Software, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix 1

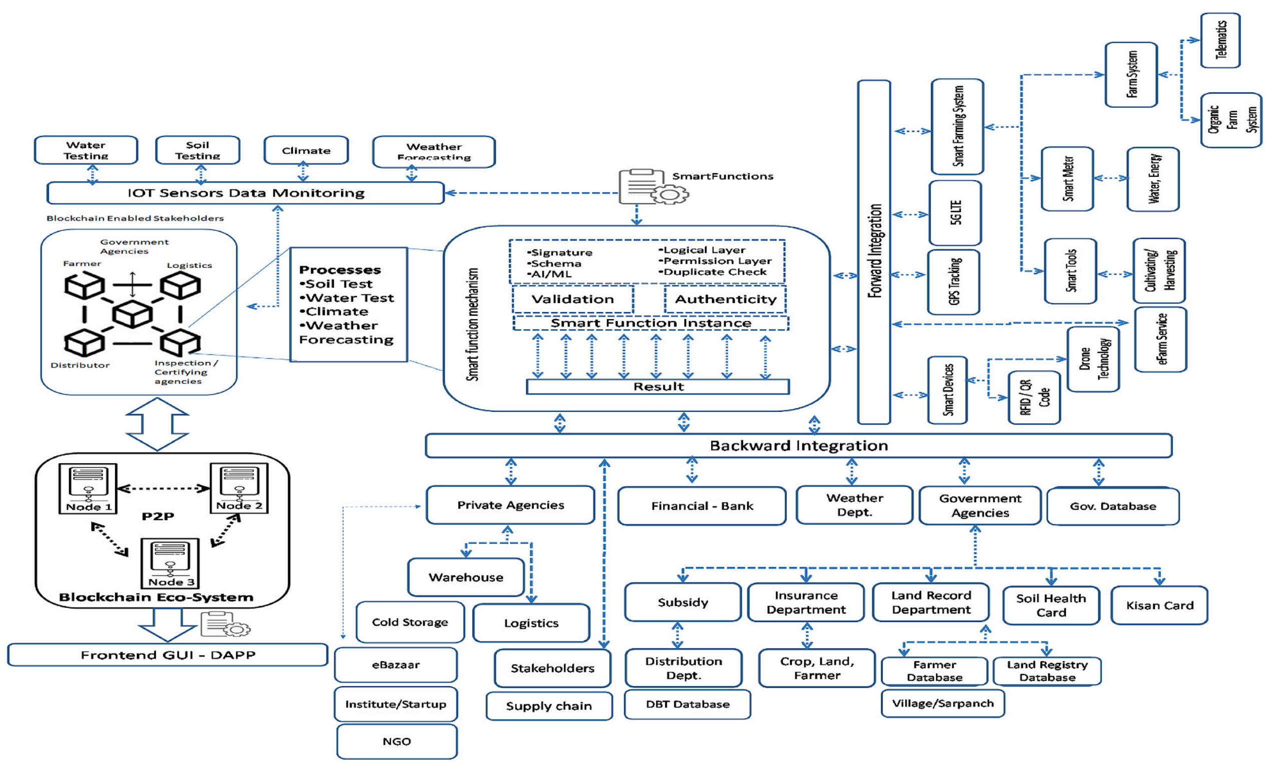


Figure A.1. The integration of blockchain and IoTs application in precision farming systems for backward and forward integration.

Appendix 2

Table A.1
A comparison of selected distributed ledger technologies (DLTs)

Blockchain example	Focus	Developers and managers	Tokens (basic unit of exchange)	Speed (transactions per second)	Coding language
Bitcoin	Digital cash system	Community of code developers	Bitcoin	7	C++
Ethereum	Smart contract	Ethereum Foundation	Ether	15	Solidity
Ripple	Connecting different payment systems	Large venture-based start-up	Ripples (XRP)	1,500	JavaScript
NEO	Smart contracts	Onchain	NEO, GAS	1,000+	C#, NET
Stellar	Unbanked	Community of code developers	XLM	1,000	JavaScript
Hyperledger Fabric	Smart contracts	Linus foundation-backed project	NA	Depending on chosen type (max. 700)	Golang
EOS	Smart contracts	Community of code developers	EOS	3,000+	C++

Source: Sylvester, G. (2018) in UN-FAO & ITU.

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