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Smart Agriculture Blockchain Applications

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HIGHLIGHTS

- Blockchain can revolutionize agriculture by enhancing transparency, traceability, and efficiency in the food industry.
- Blockchain enables secure tracking of product movement, ensuring data and food safety, and boosting consumer confidence.
- Real-time data from blockchain helps farmers make informed decisions on crop yields, weather, soil health, and animal welfare.
- Smart contracts on blockchain can automate insurance payouts, optimize soil health, create decentralized markets, and support environmentally friendly farming practices.

Abstract

Smart Agriculture is a combination of AI, Cloud Computing, and IoT that revolutionizes farming efficiency and sustainability. It successfully addresses the developing worldwide request for food production through expanding crops, optimizing inventory management, minimizing food waste, and improving the safe consumption of food. Precision agriculture, facility agriculture, and order agriculture form the core components of smart agriculture. Each one of them concentrates on specific areas of farming processes, altogether contributing to enhancing farm productivity and efficiency. The integration of blockchain technology further amplifies these benefits. Blockchain's decentralized data storage ensures data integrity and accessibility while mitigating risks associated with centralized systems. In supply chain management, blockchain enhances logistics, quality control, and risk mitigation, while in livestock management, it facilitates welfare tracking, secure identification, and grazing oversight. This study presents an in-depth review of blockchain-based smart agriculture implementations, emphasizing areas such as supply chain management, food safety, traceability, and stock management. These domains have demonstrated substantial benefits from blockchain integration. While previous research has explored various aspects of smart agriculture, an increasing number of studies highlight the supply chain as a key area of focus. The paper also highlights emerging opportunities, including the development of hybrid blockchain models to balance transparency and scalability. Additionally, blockchain-based auditing systems are identified as a

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promising tool to promote environmentally sustainable farming practices. Addressing these advancements can ensure sustainable food production, improve data management, and foster eco-friendly agricultural methods. This research underscores the transformative potential of blockchain in smart agriculture and provides a roadmap for future exploration and innovation, paving the way for sustainable and efficient farming practices.

Keywords: Blockchain; Food safety; Food traceability; Smart agriculture; Supply chain

1. Introduction

Smart Agriculture is an emerging technology that involves the integration of Artificial Intelligence (AI), Cloud Computing and the Internet of Things (IoT) in farming processes to enhance both productivity and sustainability. The fast-growing global population has led to a surge in demand for food production, making smart agriculture crucial. According to the Food and Agriculture Organization (FAO), food production must increase about 70% to sustain more than 9.1 billion people by 2050. For example, the imports of cereal products into the developing countries must increase three times to reach 300 million tons by 2050, thus the production amount in those countries needs to raise by 100% (High-Level Expert Forum, 2009). Smart agriculture can help close this gap by increasing crop yields, reducing waste, improving efficiency, and enhancing food safety.

The World Resources Institute’s (WRI) research on sustainable food for the future, as outlined in research (Searchinger et al. 2018), highlights the need for the implementation of several solutions together to achieve food sustainability. Smart agriculture can offer multiple solutions presented in the WRI research. It can help reduce food loss and waste, avoid competition for crops and land, grow livestock and pasture productivity, manage water and soil, adapt to climate change, and improve manure management.

The components of smart agriculture include precision agriculture, livestock and free-range monitoring, smart irrigation, supply chain management, information storage, crop insurance and product distribution. These components constitute Cyber-Physical Systems (CPS), which integrate physical devices with computing systems to optimize farming processes.

The integration of blockchain technology into smart agriculture is a promising solution to address many problems in the agriculture industry. In the past decade, researchers have proposed many systems for smart agriculture that utilize blockchain technology. The goal behind integrating blockchain technology with smart agriculture is to create a transparent, secure, and tamper-proof system that can track the entire lifecycle of food production, from farm to table.

There are three main sectors—agriculture, food processing, and distribution— primarily responsible for gathering data on food items. Consumers increasingly seek traceability of food products throughout the supply chain, emphasizing food quality. Supply chain entities are now seeking to earn consumers' trust by providing accurate information, adhering to standards of credibility, integrity, and quality. Regulatory bodies have introduced standards to enhance transparency and traceability in the food supply chain. A shift from centralized to distributed systems is underway to leverage benefits such as fault tolerance, scalability, and improved storage (L.B. 2022).

In smart agriculture, many surveys have been conducted over the past decade. Krithika L.B. (L.B. 2022) concentrated on existing research within specific subfields of agriculture, including smart agriculture. Other surveys have examined technology acceptance in smart agriculture (Thomas et al. 2023). As this field continues to evolve, researchers are increasingly directing their focus towards the implementation of systems such as the Internet of Things (IoT) in shaping the future of smart agriculture (Ahmed et al. 2022; Quy et al. 2022; Shaikh et al. 2022; Sinha and Dhanalakshmi 2022). However, this integration raises significant security concerns, prompting researchers to delve into the associated security and privacy challenges in smart agriculture (Ahmadi 2023; Basharat and Mohamad 2022). Moreover, some researchers have explored the potential applications of blockchain in the context of smart villages (Kaur and Parashar 2022). This paper offers a comprehensive overview of the constituents of smart agriculture, with particular focus on the relationship between smart agriculture and blockchain technology. Furthermore, it highlights the advantages of integrating blockchain technology into smart agriculture and provides insights into its potential applications within the agricultural sector. The paper also classifies blockchain applications across all domains of smart agriculture and provides a detailed discussion of their implementation.

The rest of the paper is arranged as follows. Section 2 will provide an overview of the components of smart agriculture. Section 3 explores blockchain technology and its relationship with smart agriculture. Blockchain-based smart agriculture implementations are given in Section 4. Finally, Section 5 concludes the paper with a discussion of the potential future directions of smart agriculture and blockchain integration in agriculture.

2. Smart Agriculture

Among all industries, agriculture stands out as one of the most crucial. Its production is vital for the economy and plays a pivotal role in ensuring defense, nutrition, and health for populations. Moreover, agricultural production is indispensable for the planet's sustainability. With the world's population increasing daily, the demand for agricultural products is on the rise (Alam 2023).

Bogoviz et al. (Bogoviz et al. 2023) explained the disparities between traditional and smart agriculture. Farmers adhering to traditional methods for crop sowing, cultivation, and harvesting often struggle to efficiently utilize water resources and human labor. For instance, different crops require distinct watering schedules and methods. Advancing technologies, such as wireless sensor networks, enable the detection of water requirements, facilitating tailored water planning for different crops in a field. The utilization of microelectromechanical systems (MEMs) enables precise control over water amounts. These methodologies underscore the importance of integrating intelligent systems.

Smart agriculture offers real-time monitoring capabilities, reduces reliance on human labor, and automates the detection and provision of essential resources such as water, fertilizer, and sunlight. Smart agriculture systems, incorporating ubiquitous computing, wireless ad-hoc sensor networks, radio frequency identity detection, cloud computing, data analytics, remote sensing, context-aware computations, the Internet of Things and blockchain (Kumar and Dwivedi 2023), have already permeated our daily lives (Ojha et al. 2015).

Furthermore, these systems optimize various aspects including crop development, field monitoring, greenhouse gas tracking, production management, and crop protection. However, they operate with devices characterized by low power consumption, limited memory capacity, and modest computational capabilities (Atalay 2023).

Consequently, smart agriculture is the application of advanced technologies such as remote sensing, communication, and data processing in agriculture to improve productivity. It is a rapidly growing area that can revolutionize the way agriculture has been handled from field to consumer. Smart agriculture development approaches are examined under three main categories in the literature, considering the place of agriculture and the agricultural actions taken. These are precision agriculture, facility agriculture and order agriculture (Yang et al. 2021). In Europe, order agriculture closely resembles contract agriculture (Atalay 2023).

2.1 Precision Agriculture

To enhance soil quality and productivity, farmers can implement a range of targeted interventions, a practice commonly referred to as precision farming. This is made feasible by advancements in increasingly sophisticated technologies. The term "precision" is aptly used because these cutting-edge tools allow for precise interventions to be executed at the right location, at the right time, and with exceptional accuracy, tailored to the specific needs of individual crops and areas of land (Raj et al. 2021). The emergence of smart farming and precision agriculture represents a groundbreaking innovation within the agricultural sector.

These technologies automate farming processes with the goal of achieving both high yield quantities and quality, thereby promoting food sustainability (Kwaghtyo and Eke 2023).

Precision farming is carried out in rural areas. Because agriculture is done outdoors it is affected by climatic conditions. This agricultural approach optimizes the timing and amount of water, fertilizer, seed, and pesticide with a focus on increasing the targeted product yield and protecting the agricultural ecological environment. Precision Agriculture utilizes data from multiple sources to optimize the farming process by utilizing sensors to keep track of any environmental changes, and then using machine learning algorithms to examine the data gathered. This provides valuable information on the condition of crops, helps determine the optimal approaches for planting, watering, and fertilizing, and reduces environmental impact.

Wireless sensor networks (WSNs) play a key role in this farming approach. The agricultural data (environmental data, crop development and health status data) collected from the different low-energy sensors lowers the risks in the precision farming process and enables the implementation of effective agricultural management (Srbinovska et al. 2015). Integrating wireless sensor networks lies at the core of precision farming, by facilitating real-time monitoring and data-driven decision-making in agricultural practices (Dangi 2004). In addition to remote sensing methods, Geographical Information Systems (GIS) and Global Positioning System (GPS) data are used extensively in the precision agriculture approach (Ferrag et al. 2020).

Data from the field, GIS and GPS are processed to obtain useful information. In the data processing, learning-based (Machine learning, Deep learning, etc.) methods are used (Yang et al. 2021). The information obtained because of the process is used in product and production management.

2.2 Facility Agriculture

Facility agriculture represents a novel production system that utilizes artificial technology to regulate the growth environment of crops, aiming to achieve efficient production (Bi and Liu 2023). In facility agriculture, the focus is on enhancing productivity within industrial settings. In these contexts, developmental areas oversee productivity across larger time intervals and broader plantations compared to precision agriculture. The main factors in facility agriculture include capital, technological resources, and workforce. Within these facilities, various environmental factors are artificially controlled. Synthetic processes can influence planting, cultivation, and other agricultural activities (Atalay 2023).

Facility agriculture is usually carried out in industrial areas close to the city. It aims to grow high quality products efficiently. To meet the demands and needs of people in the developing world, it makes it possible to grow the desired product in controlled environments without being affected by environmental and seasonal limitations (Vijay Hari Ram et al. 2020). As in precision agriculture, remote sensing systems are used extensively.

Horticultural and animal husbandry works done using similar technologies and systems suitable for facility agriculture are also evaluated within this scope. Any product can be grown in the facility by meticulous control of temperature and air pressure, illumination, irrigation, and fertilization, using forecast models developed using historical data of the product to be grown in facility agriculture.

The most typical example is smart greenhouses. They are commonly utilized for the cultivation of vegetables, fruits, and flowers. Currently, the main sensors used encompass environmental and plant sensors. Environmental sensors typically include temperature, humidity, soil moisture, and carbon dioxide sensors (Sun et al. 2023). This approach is also used in the fields of aquaculture, plant factory, poultry and livestock breeding with the help of different sensors and specialized control systems (Yang et al. 2021).

Smart Greenhouses are automated environments that use sensors and control systems to regulate temperature, humidity, light, and nutrients. This technology ensures that plants receive the optimal conditions for growth and reduces the need for manual labor.

Livestock Breeding and Monitoring uses technology to monitor livestock health and behavior. This involves using sensors attached to animals to monitor their movement and vital signs and analyze data to detect early signs of illness and optimize food and water consumption.

2.3 Order Agriculture

The order agriculture model is implemented to integrate technological innovations into human life. In this approach, agricultural infrastructure models tailored to specific geographical regions are strategized, utilized, monitored, and overseen. These region-specific agricultural activities can be optimized by effectively managing the supply chain, integrating appropriate technologies into relevant socio-economic units, and enhancing crop storage conditions.

Solutions for industrial applications are offered by order agriculture, derived from developments in precision and facility agriculture. For instance, when optoelectronic sensors are used to monitor and analyze weed and pest growth around a specific plant, it is categorized under precision agriculture. In facility agriculture, this mechanism is implemented and evaluated to routinely monitor a specific plantation. In order agriculture, the objective is to minimize pesticide use to mitigate damage to the ecosystem (Atalay 2023).

Although product efficiency can be increased using advanced technologies, this alone cannot gain commercial value (Dalohoun et al. 2009). To prevent unconscious production and to minimize production risks, an efficient commercial model is created with the help of order agriculture, which considers the external demand for the product (Bellemare and Bloem 2018). The agricultural supply chain developed in this process.

1. It provides agricultural product transparency from field to market.
2. It prevents information imbalance between farmers and suppliers.
3. It helps to ensure the supply-demand balance in agricultural products.

It has been proposed to use the increasingly popular blockchain technology to solve the trust problem in agricultural product supply chains (Hua et al. 2018).

To implement smart agriculture, several components and requirements are necessary. These include remote sensing tools for data collection, communication systems for data transmission, data storage, and control system. Figure 1 demonstrates the data flow in a smart agriculture system.

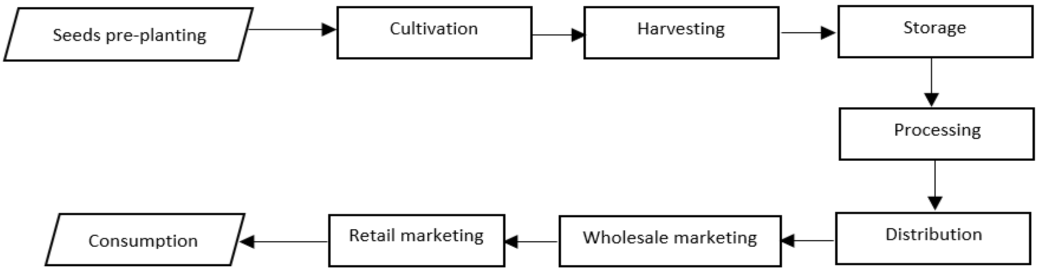

Figure 1. Data flow in food chain.

Additionally, farmers need specialized agricultural software to analyze the collected data to manage their farms depending on their needs. Smart Agriculture requires investment in technology, but it has the potential to increase crop yields and reduce resource usage.

3. Blockchain Basics

Blockchain is a distributed digital ledger technology that is designed to securely record transactions and maintain a tamper-proof record of information, which makes it resistant to fraud and hacking attempts. A blockchain consists of a series of blocks, where each block contains of a set of transactions that have been verified and recorded by the network. Figure 2 provides a simple explanation of how a transaction is added to the blockchain.

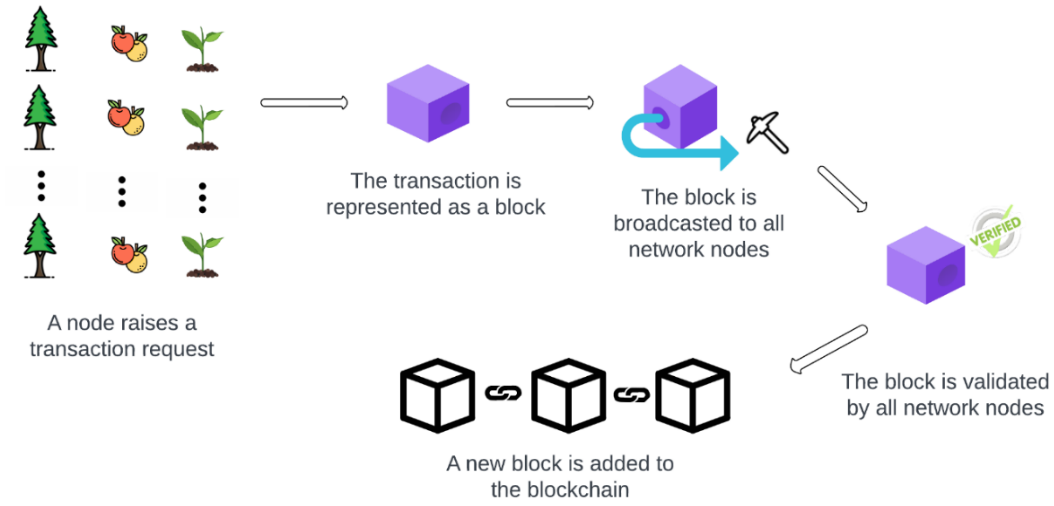

Figure 2. Transaction flow in a blockchain.

Blockchain technology serves as a robust tool for enhancing the efficiency of smart agriculture processes. In a blockchain system, users submit transactions, which are then grouped together to create a block. In a smart agriculture scenario, information about each agricultural resource, such as livestock, soil, water, plant, and seed, can be represented as a transaction. Single or multiple transactions can form a block. A block is created and verified, then it is connected to the existing chain, with the collaboration of independent parties called miners. A leader is chosen randomly among the miners to decide who will add the block to the chain. Selecting the leader can be achieved with the help of consensus algorithms. Additionally, miners must approve and accept block's proper generation before it is added to the chain.

A block includes information from the previous block to create connection between the blocks in the chain. This feature strengthens security, since modifying a single transaction would require updating all subsequent information in the chain, which is a challenging task.

Additionally, the blockchain can execute a task without third-party intervention. This is done using automated scripts called smart contracts. Smart contracts operate autonomously on the blockchain, which enables the seamless integration of these procedures during the design of the blockchain system.

Blockchain technology is highly secure and resistant to fraud. Consensus algorithms and smart contracts create a more trustworthy system by ensuring that all transactions are validated and recorded in a tamper-proof manner (Sakib 2024).

There are numerous benefits of using blockchain technology in smart agriculture. It increases transparency and immutability, improves supply chain management, and enhances food safety. Blockchain can help farmers and consumers track the origin and journey of food products from farm to consumer and ensure that the food is produced in a sustainable and ethical manner. Additionally, with its growing lists of securely linked blocks, blockchain can record sales and all data from seed planting to consumption (Patil et al. 2018).

Blockchain can help reduce fraud and corruption in the agricultural sector, leading to fair prices for farmers and improved access to markets.

4. Blockchain Platforms and Technologies

This paper explores the integration of blockchain in smart agriculture, highlighting specific platforms and technologies that address agricultural challenges.

4.1 Blockchain Platforms

1. Ethereum: Known for its smart contract functionality, Ethereum enables automated solutions for crop insurance (Omar et al. 2023), land registry (Shrivastava and Dwivedi 2023), and food traceability (Kechagias et al. 2023). This reduces dependency on intermediaries while enhancing transparency and efficiency.
2. Hyperledger Fabric: A permissioned blockchain platform, Hyperledger Fabric facilitates secure data sharing (Hu et al. 2024) and ensures transparency in supply chains. It has been widely adopted for improving accountability (Srikanth et al. 2024) and managing agricultural resources.
3. Hyperledger Sawtooth: a blockchain framework designed for enterprise use, brings transformative benefits to smart agriculture by enabling secure, decentralized, and efficient management of agricultural operations. It enhances supply chain traceability (Gkogkos et al. 2023), ensuring the authenticity and quality of agricultural products by recording every transaction on an immutable ledger. This provides transparency and builds trust among consumers, farmers, and stakeholders.
4. Multi-Chain: A blockchain platform designed to facilitate the deploying of customized permissioned blockchains. For example, the FoodFresh model (Stangl and Neumann 2023), which significantly enhances smart agriculture by enabling controlled data transparency and secure collaboration across agricultural supply chains. Multi-Chain can also help enhancing land record management in smart agriculture (Kumar et al. 2024).

4.1 Implementation Techniques

To harness blockchain effectively, the following implementation techniques have been adopted:

1. Smart Contracts: They automate processes like crop insurance payouts based on predefined conditions such as weather data or yield thresholds. For example, (Loukil et al. 2021) proposed CioSy, a blockchain-based collaborative insurance system that automates policy processing, claim handling, and payment through smart contracts, enabling peer-to-peer insurance while ensuring transparency and reducing operational costs.
2. IoT: IoT sensors combined with blockchain platforms monitor environmental conditions like temperature, humidity, and soil moisture (Ahmed et al. 2024). IoT-based aquaculture systems can leverage advanced monitoring technologies to track vital water quality parameters such as temperature and dissolved oxygen in real time, ensuring optimal fishpond conditions (Prapti et al. 2022).

5. Blockchain Applications on Smart Agriculture

Blockchain technology provides secure and temper-proof transactions without intermediaries and can transform various industries, including agriculture. There are many benefits to using blockchain technology in smart agriculture. These benefits include food safety, data transparency, traceability, and efficiency in supply chain (Yadav and Singh 2019). It also makes it possible to securely save information about the farms on blocks (Xiong et al. 2020).

In today's world, consumers are increasingly demanding more transparency in the food supply chain. They want to know where their food comes from, how it is produced, and whether it is safe to consume. However, the global food supply chain is complex, which makes it difficult to track and trace products. Blockchain technology provides a solution by creating a secure, transparent, and immutable ledger that can track the entire food supply chain. It can ensure that the food is produced and transported in compliance with regulations and ethical standards. Additionally, blockchain technology can improve farmers' livelihoods by giving them better access to sales, insurance, farm overseeing and other services.

Blockchain technology can provide transparency and traceability in the supply chain, so that farmers can track the movement of products from the farms to the consumers. This also provides consumers with information on the safety and quality of the food they are consuming, thus improving their confidence. In addition, blockchain helps farmers manage their farms more efficiently by providing them with real-time data on crop yields, weather conditions, and soil health. This data helps farmers make better decisions about crop selection, fertilization, and irrigation, and thus improving their productivity and profitability.

Accordingly, blockchain technology can be used in various areas of smart agriculture, including:

1. Production: It refers to the agricultural product that is produced using technology. Smart agriculture uses technology to produce more food and retain its sustainability.
2. Storage: It refers to the use of technology to optimize the storage of agricultural products. Smart storage can also involve optimizing inventory management and reducing waste.
3. Stock: It refers to the land, farm, livestock. Smart agriculture uses technology to manage these assets to improve productivity, sustainability, and profitability.

5.1 Production

Blockchain technology can be implemented in food supply chain and food traceability. Figure 3 shows where this technology can be implemented in food production.

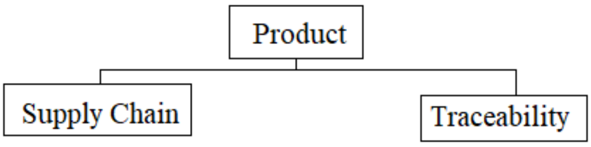

Figure 3. Areas where blockchain can be implemented in production.

5.1.1 Food Supply Chain

Supply chain is divided into two entities: organizations or individuals that are directly involved in products, services, finances, and data from seed planting to consumption (Mentzer et al. 2001). Food is one of the most important aspects that needs to be considered from a society perspective. It is the pillar of health, happiness, and economy. However, when it comes to delivering the product to consumer, the priority to consider is the security and personal safety of individuals (“Food Supply Chain Manag.” 2007). Some blockchain applications in agri-food area are:

Chatterjee et al. (Chatterjee et al. 2023) explored the integration of Internet of Things (IoT) technology within Industry 4.0, underscoring its diverse applications across sectors like banking, manufacturing, healthcare, and government. Industrial IoT (IIoT) is specifically highlighted for its role in leveraging IoT services to link existing industrial processes with emerging technologies such as smart sensors, robotics, and artificial intelligence, with a particular focus on enhancing supply chain management. The rising consumer demand for organic food products has underscored the significance of traceability and transparency in food supply chains. Consequently, regulatory bodies are advocating for enhanced standards, prompting a shift from centralized to distributed systems to bolster fault tolerance and scalability. The design of food supply chain systems is examined through the lens of a hierarchical location problem, with recent research exploring optimization strategies. Additionally, they introduced a blockchain-based food supply chain system that was tailored for the agro-food industry. Their paper emphasized the system’s advantages over traditional management methods, especially in terms of traceability and security. However, the proposed model does have some limitations, including scalability issues and a susceptibility to certain types of attacks. These limitations require future enhancements.

Mandela et al. (Mandela et al. 2023) introduced the complexities confronting agricultural supply chains in Andhra Pradesh, India, within the broader context of ensuring food safety and quality. They proposed using consensus algorithms to develop a blockchain-based query processing system, with the intention to augment transparency, accountability, traceability, and efficiency throughout the agricultural supply chain. Moreover, they underscored potential benefits, such as enhanced market access and sustainability. The study also covered precision agriculture, emphasizing its use of advanced technologies to enhance productivity and minimize waste, alongside the growing challenge of ensuring food safety. It highlights the significance of blockchain technology in addressing these challenges and bolstering food safety, traceability, and environmental sustainability. The authors identified consensus algorithms as pivotal for upholding the integrity and security of blockchain transactions, which would facilitate the establishment of dependable and transparent supply chains for smart agriculture.

In a study conducted by Leng et al. (Leng et al. 2018) they identified and discussed significant problems in the Chinese public service platform related to agriculture. and proposed a solution using public blockchain technology. This included problems such as a lack of resource matching mechanisms, low utilization rates, and suboptimal system performance. These issues all increased transaction costs and discouraged users from engaging with the platform. The authors also discussed concerns about transaction security, transparency, user privacy, and platform credibility. They suggested integrating a two-chain public blockchain system tailored for agricultural business resources into the existing platform. This integration would provide technical support, create a functional environment, and enhance the usage rate, credibility, and effectiveness of the platform while ensuring secure handling of diverse types of data.

One crucial procedure in Agri-food is quality measurement. Lucena et al. (Lucena et al. 2018) addressed the quality management of the grain throughout the transportation chain using blockchain to bring more efficiency and resilience to this process. They presented the Grain Exporters Business Network 'GEBN,' which is an enterprise that collects information from quality assurance processes and then provides data for diverse business partners of the Brazilian GEBN. It is made up of various stakeholders, such as grain producers, local credit unions, warehouse companies, trading exporters, agrochemical companies, freight forwarders, and ports authorities. The platform can assist producers to trace the products stored in warehouses.

Saberi et al. (Saberi et al. 2019) examined the application of blockchain technology for promoting sustainability within supply chains. With increasing pressure from both local and global governments and communities to achieve sustainability goals, there is a growing need to explore how blockchain can address supply chain sustainability. The authors proposed a transformation of traditional supply chains into blockchain-based systems, which involved four main entities: a registrar providing actor identification, a standards body defining blockchain guidelines and technical requirements, a certifier authorizing parties to participate in the supply chain, and several factors such as manufacturers, retailers, and customers (Project Provenance Ltd 2015). They also put forward future research suggestions to overcome barriers and promote the adoption of blockchain in supply chain management.

5.1.2 Traceability

Food traceability means following and tracing the documentation and linkage of all stages in the supply chain, both forwards and backwards, through which a food product and its ingredients move from production to distribution (FDA 2022). The utilization of blockchain in traceability systems ensures the reliability and authenticity of shared information (Tian 2016).

Researchers have been exploring the application of blockchain technology to enhance food safety. One notable study by Lin et al. (Lin et al. 2019) introduced a blockchain system to both prevent the tampering of food data and to address the shortcomings of the existing traceability systems. The authors developed a prototype system that combined blockchain and Electronic Product Code Information Services (EPICS) to trace the products. This distributed system allowed for the creation and sharing of visibility data, ensured the security of sensitive information through tamper-proof features while maintaining scalability. The integration of an enterprise-level smart contract ensured the confidentiality of business data and authenticated the identity of the enterprise. By leveraging the advantages of the EPCIS specification, which included ObjectEvent, AggregationEvent, QuantityEvent, and TransactionEvent, the proposed system demonstrated potential for effectively addressing food safety concerns.

Ferrández-Pastor et al. (Ferrández-Pastor et al. 2022) investigated the potential of integrating Internet of Things (IoT) facilities and ambient intelligence paradigms to optimize agronomic processes, with a focus on the hemp industry., Their goal was to enhance both traceability and security. They proposed a comprehensive model that amalgamates agricultural expertise, blockchain technology for value chain planning, and IoT protocols for digital traceability. The efficacy of the model was demonstrated through a proof-of-concept implementation, highlighting its ability to deliver tamper-proof and transparent traceability services. Additionally, the article underscored the significance of integrating information technologies to address consumer concerns regarding product safety, quality, and origin. Their proposed model offered numerous benefits, including the active engagement of agricultural experts, enhanced traceability, improved data security, process optimization, and cost savings through smart contracts. However, it also presented new challenges, such as ensuring seamless integration into existing systems, providing intuitive interfaces for farmers and technicians, and ensuring ongoing maintenance and updates. Overall, the article presented a promising approach to advancing traceability and resource optimization services in agricultural production processes, with the potential for future extensions and enhancements.

A study conducted by Sezer et al. (Sezer et al. 2022) discussed the critical aspects of traceability in supply chain management, underlining the pivotal role of customer trust. It pointed out the inadequacies of the existing frameworks in delivering efficient traceability, real-time data, and privacy safeguards. The article introduced a supply chain traceability framework that leveraged smart contracts to safeguard privacy from external entities. This framework incorporated a digital signature and verification mechanisms to uphold data integrity and authenticity. Thus, offering both anonymity and traceability according to user preferences. Furthermore, it discussed how blockchain technology enhances transparency and trust by securely storing transaction data in an immutable manner. The article also delved into the complexities of traceability in supply chains and stressed the need for systems that ensure product tracking while maintaining trust and privacy. The proposed framework, grounded in permissioned blockchain architecture, sought to strike a balance between anonymity and transparency while ensuring traceability and privacy through on-chain and off-chain smart contracts. Their experimental findings suggest that the framework presents a user-friendly and auditable model for supply chains. Future research endeavors include addressing space complexity using side chains, implementing lightweight blockchain architectures for IoT devices, and exploring real-world applications of the proposed framework.

Lin et al. (Lin et al. 2018) proposed a secure food traceability system that utilized blockchain technology and IoT devices to address food safety concerns. The system's goal was to track and monitor the entire food production process, from seed cultivation to selling, and to reduce human intervention using IoT devices to record and verify. In their system, a combination of the traditional Enterprise Resource Planning (ERP) legacy system and a new IoT system was employed. Mobile phones served as a portal or blockchain thin node for farm companies, logistic companies, and customers to access the data stored in the chain.

Another study by Tse et al. (Tse et al. 2017) proposed blockchain technology as a solution to improve food safety standards in response to rising concerns in China. The current food safety systems failed to meet the required standards, which resulted in products classified as unsafe for trade. To address this problem, the authors suggested blockchain to secure information within the food supply chain. They applied tailored theoretical methods and conducted a market analysis to develop an efficient and reliable solution for managing agricultural product safety in China. Through the implementation of blockchain, the study sought to enhance the quality and safety of food products in the country, mitigating potential health risks and improving the overall quality of life.

Feng Tian (Tian 2016) proposed a food safety system that used blockchain technology to achieve transparency and openness in the food supply chain. This system tracked products in real-time using logistic companies, which eliminated the need for a centralized organization to oversee food safety information. All members of the system had access to an information platform, and blockchain ensured the integrity of the food data. The system focused on two categories of agri-food: fresh fruits and vegetables, and meat. It utilized RFID technology to acquire and share data throughout the entire production process, while blockchain certified the reliability of the information shared within the system. Overall, the system provided a secure and traceable platform for all members of the food supply chain.

Caro et al. (Caro et al. 2018) evaluated the effectiveness of AgrilockIoT, a system that utilized both IoT sensing devices and blockchain technology for agricultural traceability. The system generated digital values through the IoT devices and stored them securely in a blockchain, creating transparent and unchangeable records. The study found that using a permissioned blockchain, instead of a public blockchain, significantly improved the performance of the smart agriculture system. The permissioned blockchain had lower latency compared to the public blockchain, and thus offered faster and easier operation. Additionally, the public blockchain consumed approximately 50 percent more resources, resulting in poorer performance.

In a study conducted on using blockchain technology to track wood electronically throughout the supply chain. Figorilli et al. (Figorilli et al. 2018) implemented a blockchain architecture to enable traceability of the wood supply chain, simulating processes from tree cutting to the sawmill in Italy. Open source IoT devices collected data on tree species, date, position, number of logs, and commercial information, which was stored in a centralized database using a specific forest operations app. The blockchain system allows retrieval of historical information by tracing each tree's journey. Activation of the blockchain involved an activation code and data transmission, synchronized with a remote server. Two steps were required: authorization through Azure Blockchain workbench and data formatting, verification, and writing onto the blockchain. The application ensured that no unauthorized logs were inserted and provided progress feedback during the synchronization process.

Kumar and Iyengar (Kumar and Iyengar 2017) presented a case study of the application of blockchain technology to the rice supply chain. When participants in the chain registered in the system, they had unique identities and digital profiles which were stored in the blockchain. The rice supply chain has five phases: production, procurement, processing, distribution, and retailing. Blockchain was used to ensure traceability, combat fraud, and reduce errors by documenting all events that occurred in the chain. Each time the rice changed location, the information was recorded on the blockchain, creating a permanent record of its journey from the manufacturer to the consumer. The authors demonstrated how blockchain technology enhanced product safety and improved the efficiency of the rice supply chain through comprehensive traceability, event recording, and monitoring of rice quality and security.

5.2 Storage

Food products like rice and beans must go through a series of procedures such as production, grading, storage, and transportation before reaching the market. Throughout this process any fraudulent or tampered steps could pose significant risks to food safety. Utilizing IoT for the real-time tracking of these procedures can ensure that the entire process is traceable. However, it is important to note that traditional storage methods are vulnerable to manipulation or destruction of the stored data. To address this problem, blockchain technology offers a safe and decentralized database consisting of a series of secured blocks of data. Once a block has been confirmed and incorporated into the chain, it cannot be altered unless someone has control over more than half of the nodes simultaneously. This feature guarantees the reliability of the blockchain as data storage.

The agricultural process begins with seed storage, which can significantly impact seed quality and production. Thus, it is crucial to monitor seed storage. To ensure better control of the market price, the distribution and market prices must be properly monitored. To have effective monitoring, agriproducts must be traceable from seed storage to the consumer. The availability of verifiable data for the agriproducts not only increases transparency but also enables monitoring and manipulation of the system. Addressing these challenges is essential for ensuring a consistent supply of food products without any shortages.

There have been many studies conducted in agricultural data storage to investigate the potential applications and advantages of integrating blockchain technology. For instance, Xie et al. (Xie et al. 2017) designed a secure data storage scheme for food tracking that was based on blockchain technology. In this system, agricultural products were equipped with an IoT sensor module that acquired data in real-time and uploaded it to the server. The server used a double-chain storage structure consisting of two interconnected main and secondary blockchains to automatically store the data in the blockchain. This certified that agricultural tracking data could be stored securely using blockchain, thereby ensuring better food safety.

Zhang et al. (Zhang et al. 2023) introduced a blockchain-based traceability model for the grain and oil food supply chain, tailored for its inherent complexities and challenges. An outlier detection model was developed to ensure accurate data collection from IoT devices, which exhibited excellent performance in outlier detection. A storage model that combined blockchain with database and IPFS was introduced to improve storage efficiency, and to reduce pressure on the blockchain network. A data recovery mechanism was implemented to ensure the timely recovery of lost or damaged data, which enhanced the system fault tolerance. Experimental results demonstrated the effectiveness of the proposed model, with average query latencies indicating efficient data retrieval. Finally, a blockchain-based grain and oil food supply chain traceability system was designed and implemented using Hyperledger Fabric, which allowed for multi-source data uploading, lightweight storage, and data recovery in the supply chain.

To ensure the secure exchange and storage of vast amounts of remote sensing data, Zou et al. (Zou et al. 2023) presented a decentralized system utilizing blockchain technology. Because conventional centralized systems are susceptible to attacks, there is a risk of data loss. Distributed Ledger Technology (DLT) provides security, traceability, and tamper-proof capabilities suitable for remote sensing applications. However, there were some challenges integrating remote sensing data into blockchain networks due to its large volume and spatiotemporal characteristics. To address these challenges, they proposed a multi-level blockchain architecture. Remote sensing data was stored in the IPFS network, with its hash value uploaded to the Ethereum chain for public access. This distributed data storage approach improved security, facilitated information exchange, and increased data management efficiency. Additionally, the paper suggested a data storage security solution leveraging multiple blockchains to offer accountable and distributed storage. Utilizing the Ethereum blockchain platform, the prototype system was designed and simulated, displaying its effectiveness in terms of data storage speed, traceability, security, and availability. However, some challenges remained, such as the need to encrypt data for further security enhancement.

Lin et al. (Lin et al. 2017) proposed a storage security approach using blockchain. The continued progression of Moore's Law, Kryder's Law, and Nielsen's Law, which describe the increasing speed of data processing, decreasing costs of data storage respectively, combined with increasing bandwidth, suggests that blockchain technology can play a vital role in the agricultural industry. As a decentralized network, blockchain has the potential to democratize transactions and processes in the industry, making it the next evolutionary step for traditional Information and Communication Technology (ICT) based farming systems and e-agriculture initiatives. Through blockchain technology, agricultural and environmental monitoring data can be stored in a distributed cloud. This will lead to the achievement of sustainable agricultural development with the help of transparent data and ICT.

The proposed system was used for managing and sorting food monitoring information. They put forward a model of an ICT-based system which included a blockchain infrastructure. They suggested adding water quality monitoring data into the blockchain. Miner nodes in the network contributed its equipment to validate the blockchain and compile the complete water data.

Another study by Pranto et al. (Pranto et al. 2021) proposed the use of IoT to enhance the movement of vital data within the agricultural system. The IoT devices kept an eye on the quality and state of products stored in warehouses while providing information during the cultivation process. The monitored data was then securely saved in a blockchain, and a smart contract took care of automation, event triggering, and the enforcement of necessary terms and conditions for all parties involved.

5.3 Stock

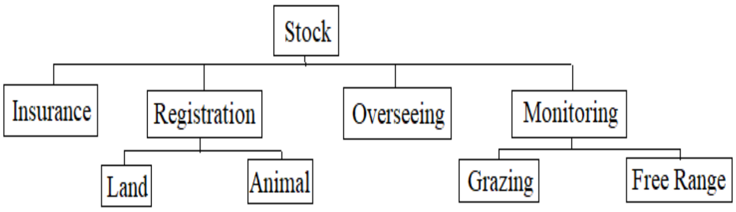

Figure. 4. Stock management in smart agriculture.

5.3.1 Crop Insurance

Farmers often do not trust insurance companies and fear delays or non-payment of claims, which makes crop insurance systems complex and challenging. However, some studies have suggested affordable and efficient crop insurance solutions that could benefit many farmers. One proposed solution was a blockchain-based crop insurance system, which provided a new infrastructure for storing, validating, and securely transferring data. Blockchain technology would ensure that the data is stored without manipulation and eliminates the need for third parties. This makes it a reliable solution for crop insurance.

Crop insurance is divided into two categories: yield protection insurance and calamity-based insurance. In yield protection insurance farmers can register a claim if their crop yield falls below a predetermined threshold. Calamity-based insurance automatically settles claims if a crop is destroyed due to a natural disaster. It does not require farmers to file a claim. Instead, when a natural disaster is recorded on the blockchain, a smart contract automatically initiates the payment process into the farmer's account.

Agricultural production is exposed to numerous uncontrollable risks. Most of the time, farmers have limited means to mitigate these risks. The most obvious being insurance, which is hindered by the lack of private sector involvement and by complicated claim procedures that discourage farmers from exploring new crops. In India, the current crop security system does not adequately address the escalating risks farmers face. To solve this problem, Iyer et al. (Iyer et al. 2021) proposed a decentralized peer-to-peer crop insurance framework to protect farmers' interests. This framework eliminated intermediaries and provided a secure, standardized, and transparent system that ensured all stakeholders had access to the necessary information. Through blockchain technology, the system promoted trust in a trustless environment and allowed for farmers and private investors to form a contract.

Omar et al. (Omar et al. 2023) presented an innovative approach to crop insurance using blockchain technology to tackle challenges like complexity, inflated costs, and a lack of trust in the conventional methods. Their blockchain-based crop index insurance solution recorded transactions and data exchanges on an immutable ledger, which ensured transparency, trust, and accountability. Smart contracts can streamline claim processing, reduce fraud and settlement delays, and lower costs by removing intermediaries. Their solution democratized crop insurance and expanded access to a wider range of farmers. It also included those in low-income countries. Their paper underscores the importance of tailoring the solution to meet the needs of smallholder farmers in developing nations and highlights the advantages of decentralization and blockchain in improving transparency and trust between farmers and insurers. The authors make their smart contract code openly available and outline plans for future work to automate additional insurance processes and tackle scalability and governance challenges within the blockchain landscape.

Jha et al. (Jha et al. 2021) proposed a decentralized platform for executing contracts and storing the results of crop insurance processes using smart contracts. This system helped insurance companies detect fraud and evaluate claims through smart contracts, which are more secure and less prone to exploitation than traditional insurance systems. Blockchain allowed for secure coordination between insurers, and records were stored on a secure distributed ledger. This made any malicious activity clear and then halted the transaction. The major stakeholders in this system included farmers, smart contracts, and insurance providers. The farmers provided personal data, crop information, and land coordinates for verification by insurance providers. Once verified, the insurance policy details were written on the blockchain as a smart contract hosted on a cloud platform, and insurance providers could verify weather conditions and determine the amount of money to be paid to the farmer in case of natural calamity.

The insurance industry is facing challenges related to the processing time, security, and settlement time of payments. However, blockchain technology can provide solutions to these problems. Bai et al. (Bai et al. 2022) proposed a novel approach that leveraged blockchain technology's immutability and integrity features to enhance the insurance process. They proposed a use case of blockchain and IoT technology to develop a transparent and secure framework that could improve processing time, security, and settlement time of payments. The proposed system sought to provide a more efficient and reliable insurance service through the reduction of the time delay in a claim settlement. The system assigned a unique ID to each participant, allowing them to read and write data on the blockchain. This made it possible for all stakeholders to upload all relevant information related to the insurance policy. To capture data from agricultural land, IoT devices and various sensors such as soil, moisture and fire sensors are then deployed. The use of IoT devices removes human interaction in the process.

5.3.2 Registration

Land registration is susceptible to tampering in various countries. Blockchain technology offers significant benefits when it comes to maintaining asset registers like property, vehicles, and contracts. Blockchain has specifically gained prominence in land registration due to its ability to address fraud concerns and provide a trusted and transparent system for storing and transferring data. By decentralizing and standardizing land registration records, blockchain reduced the need for intermediaries, enhanced trust in the transacting parties' identities, improved process efficiencies, and reduced the time and cost associated with registration (Deloitte 2018). Thus, technology must continue contributing to this field.

5.3.2.1 Land Registration

According to HernandoDe Soto out of the 7.3 billion people in the world, only around 2 billion possess legal and effective documentation confirming their ownership of an asset. The lack of legal record of ownership makes it impossible to use these assets as collateral to obtain credit or to transfer a portion of property as an investment. This implies that individuals cannot fulfill their potential to create credit, because their assets may be owned without proper documentation. Thus, HernandoDe Soto emphasizes the importance of effective land administration systems to ensure that property ownership is accurately recorded and recognized by the law (Barbieri and Gassen 2017).

In 2015, it was reported that the Government of Honduras was collaborating with Factom and Epigraph to create a land registry system using blockchain technology. This initiative sparked discussions and debates about the potential applications of blockchain in land administration (Anand et al. 2017). According to Anand et al. (Anand et al. 2017), some potential applications of blockchain technology included registering title deeds, creating time-stamped transactions, providing transparent governance tools for multiple parties, creating a tamper-proof recording system, establishing a disaster recovery system, and offering restitution and compensation in post-conflict zones.

Barbieri and Gassen (Barbieri and Gassen 2017) argue that the use of blockchain technology for land registers is still not fully understood. This is especially true when it comes to the well-established interplay between cadaster and land register, and the role of notary in the framework of preventive administration of justice. They suggested that advocates of blockchain solutions may not fully understand these aspects. Thus, from their perspective, blockchain technology appears to be useful only in the context of machine-to-machine communication at present.

Vos et al. (Vos et al. 2017) examined the potential of replacing an existing land administration system with a blockchain-based alternative. They highlighted the technical and administrative requirements that must be met for a blockchain-based land administration system to be successful. Blockchain technology can be used to archive transactions and to secure their content by storing transaction data on the blockchain. They suggested that blockchain technology could be useful in countries without a reliable electronic system for transferring ownership. However, they did note that traditional database systems may be sufficient in some cases.

In considering blockchain, several principles of Good Governance can be fulfilled. For example, the transparency and efficiency of transactions can be ensured, and a tamperproof history of transactions can be maintained. Blockchain-based land administration systems can function similarly to traditional land registry systems since they keep track of property ownership and transaction records and verify the authenticity of these records. Additionally, they can ensure the accuracy and timeliness of land transactions and prevent fraudulent activities.

5.3.2.2 Animal Registration

Cho and Lee (Cho and Lee 2019) introduced an animal administration system, that utilizes blockchain technology to distinguish between animals that are preregistered or not. This system can be implemented in various areas such as animal hospitals, pet stores, animal shelters, and pet insurance policies. N-printing technology, which is like how fingerprints are used to identify humans, can be used to identify animals. This authentication process uses nose-print recognition to identify animals and connect various clients through a blockchain network.

5.3.3 Farm Overseeing

Monitoring environmental information is vital for maintaining a healthy environment. Similarly, monitoring the agri-food environment is essential for ensuring food safety. Lin et al. (Lin et al. 2017) put forward an e-agriculture system model that utilized ICT and blockchain infrastructure for water distribution monitoring at the local and regional scale. The system added water quality monitoring data to the blockchain, which was then backed up and distributed across all nodes. Each node had a copy of the water data, and a query was created for reference purposes. The provider node could later cross-reference the data in the blockchain with the backed-up data if required.

The agricultural industry has started using IoT-based greenhouse technology that enabled remote monitoring and automation. However, the security concerns related to the large-scale and widely distributed network were still significant. To address these problems, Patil et al. (Patil et al. 2018) suggested utilizing blockchain technology to secure the emerging IoT-based greenhouse technology. The system model consisted of four groups; a smart greenhouse, an overlay network for reducing network overhead and delay, a cloud storage to store data from the greenhouse devices, and end users who own, control, and remotely monitor the greenhouse through their laptops or smartphones. The proposed architecture used a lightweight blockchain-based approach, which enhanced power consumption and benefits from private immutable ledgers. The IoT devices deployed in greenhouses act as a centrally managed blockchain, which further improved the security of the system.

Mujeye et al. (Mujeye et al. 2023) discussed the potential applications of 5G technology and IoT devices in agriculture and healthcare. Their focus was on addressing security and privacy concerns through the utilization of Blockchain technology. This study outlined a research endeavor involving Illinois State University and industry collaborators, who sought to deploy a private 5G network equipped with IoT sensors for monitoring soil moisture levels on a university farm. Additionally, the project's goal was to support underserved patients in managing chronic illnesses by remotely tracking vital signs through IoT devices. The study's primary objective was to evaluate the efficacy of Blockchain in securing communications between these sensors and healthcare providers. Furthermore, it emphasized the broader impacts of the research, including enhancing healthcare accessibility for marginalized communities and tackling agricultural issues such as soil nutrient depletion and water conservation. These efforts contributed to bolstering food security for the growing global population.

5.4.4 Monitoring

5.4.4.1 Livestock grazing

The swift expansion of blockchain technology in precision agriculture has resulted in the creation of several platforms with the potential to be used for a range of agricultural activities. For example, the AppliFarm platform, established by Neovia in 2017 (ADM 2023), enabled the provision of digital evidence for animal welfare and livestock grazing. The animal sector's livestock data could be tracked through the platform, which involved the use of linked tags placed around cows' necks to identify their grazing areas. This made it possible to collect enough data to ensure high-quality grazing for the livestock. In addition, their system could be used to ensure that monitored livestock farms adhere to animal welfare requirements. The animal welfare data is integrated into the system and accessible by stakeholders whenever they need access.

5.4.4.2 Free Range

Descovi et al. (Descovi et al. 2021) presented a case study based on blockchain of the health certification of poultry farms of breeding birds in the state of Rio Grande do Sul. They then mapped it with Business Process Model and Notation (BPMN). The presented blockchain system simplified the animal sanitary control of breeding birds and demonstrated the physical and digital flow of the process and how data is stored in the blockchain.

6. Discussion and Conclusion

Blockchain technology can revolutionize the agriculture industry by improving transparency, traceability, and efficiency of the food industry. In recent years, several studies have explored the applications of blockchain in smart agriculture, highlighting its potential to transform various areas such as product supply chain, product traceability, storage, farm, and stock management.

Agricultural data should be securely stored, if it is not protected from being maliciously tampered, many risks and drawbacks are encountered, such as affecting the smart agriculture efficiency and the potential danger of compromising data integrity. Since data is written in blocks unchangeably, blockchain enables stakeholders to securely track the movement of products from the farm to the consumer, which guarantees the safety of the data as well as the safety of the food. So, by providing consumers with information on the safety and quality of the food, blockchain can improve their confidence in smart agricultural products. Additionally, blockchain technology can be used to improve productivity and profitability. It can provide farmers with real-time data on crop yields, weather conditions, and soil health, helping them make better decisions. Blockchain could also be used to track animal health records, breeding information and genetic data, and monitor animal welfare and environmental impact. Regarding insurance, blockchain could be used to create smart contracts that automatically trigger insurance payouts when certain conditions are met, such as crop failure.

Table 1. Blockchain Applications in Smart Agriculture.

Study	Classification	Problem	Technologies Used Besides the Blockchain	The Proposed Technique	How Blockchain Becomes Beneficial
Chatterjee et al. (Chatterjee et al. 2023)	Product/ Supply Chain	The rising consumer demand for organic food products	IIoT	Blockchain-based solution for the food supply system	Data Integrity and Sharing: Immutability and Decentralization
Mandela et al. (Mandela et al. 2023)	Product/ Supply Chain	Fragmentation of land in Andhra Pradesh, India / lack of transparency, storage, and processing facilities	IoT	A blockchain-based query processing system for secure supply chain	Food Safety: Transparency, immutability, and improved traceability
Leng et al. (Leng et al. 2018)	Product/ Supply Chain	Lack of adaptive rent-seeking and matching mechanism / security and transparency of transactions and platform credibility	Double chain architecture	Public blockchain of agricultural supply chain system	Agricultural resource sharing: BC provided distributed rent-seeking and matching mechanism- improved the utilization rate of agricultural business resources and credibility of the public service platform
Lucena et al. (Lucena et al. 2018)	Product/ Supply Chain	Grain quality management	Smart contracts and IoT devices	GEBN Blockchain Business Network	Quality Management: Data integrity verification for quality management purposes / Efficiency and resilience of quality measurement in grains transportation
Ferrández-Pastor et al. (Ferrández-Pastor et al. 2022)	Product/ Traceability	Integration-related challenges in the implementation of facilities based on the IoT, embedded systems, and ambient intelligence paradigms in the hemp industry	IoT	IoT and Blockchain based model for traceability: Application in industrial hemp production	Data flow security
Sezer et al. (Sezer et al. 2022)	Product/ Traceability	Poor traceability, lack of real-time data, and lack of privacy in the supply chain	Cryptography and smart contract	TPPSUPPLY: A traceable and privacy-preserving blockchain system architecture	Real-time data, data privacy, and scalability
Lin et al. (Lin et al. 2019)	Product/ Traceability	Preventing sensitive information disclosure and data tampering	Enterprise-level smart contract / off-chain database	Food safety traceability system based on blockchain and EPCIS - management architecture of on-chain and off-chain data	Data Privacy and Integrity: Sensitive business information protection / enterprise identity verification / verification of data integrity
Lin et al. (Lin et al. 2018)	Product/ Traceability	Monitoring chemical use in farming, heavy metal contamination, low-quality raw materials, and excessive additives endanger food safety	IoT devices and smart contracts	Blockchain and LoRa IoT technology-based food traceability solution	Food Safety: Tracking and monitoring the entire food production process through verification mechanism and tamper-proof advantage
Tse et al. (Tse et al. 2017)	Product/ Traceability	Potential risks to people's health and limitations in precise traceability	N/A	Blockchain technology as a potential solution for enhancing information security	Food Safety: Immutable transaction records, automated monitoring and auditing system, and food safety and certification enhancement
Zhang et al. (Zhang et al. 2023)	Storage	The redundant data storage in the grain-and-oil-food-supply chain	IoT devices, MySQL database, machine learning, and IPFS	A blockchain-based traceability model for the grain-and-oil-food-supply chain	Enabling multi-source data uploading, lightweight storage, and data recovery

Zou et al. (Zou et al. 2023)	Storage	Incorporating the large volume and spatiotemporal characteristics of remote sensing data	IPFS	A remote sensing data storage model based on a multi-chain structure blockchain architecture	Data sharing and management
Lin et al. (Lin et al. 2017)	Storage	Agricultural data security and monitoring data sharing	ICT-based system	A model ICT e-agriculture system with a blockchain infrastructure	Data Integrity and sharing: Immutability and decentralization (instead of a centralized database)
Pranto et al. (Pranto et al. 2021)	Storage	Agricultural data sharing and monitoring	Smart contracts and IoT devices	A blockchain-based IoT and smart contracts	Data Integrity and sharing: Immutability, data availability, and transparency
Omar et al. (Omar et al. 2023)	Stock/ Crop Insurance	Complexity, excessive costs, and a lack of trust in conventional crop insurance methods	IPFS and Ethereum Smart contracts	Blockchain-based crop index insurance solution using Ethereum smart contract	Immutability and Transparency throughout the insurance ecosystem
Iyer et al. (Iyer et al. 2021)	Stock/ Crop Insurance	Farmers' risk vulnerability due to insurance gaps, private sector absence, crop security, and the need for innovative insurance products	Know Your Customer (KYC) verification and smart contract	A decentralized peer-to-peer crop insurance framework	Agricultural Insurance: Promotes trust in an untrusted environment by providing data integrity – The system enables the provision of insurance coverage for nonseasonal and unusually heavy rainfall.
Jha et al. (Jha et al. 2021)	Stock/ Crop Insurance	Cost of administering insurance and the great losses due to natural disasters	Smart contracts and a cloud environment	A blockchain based affordable crop insurance solution	Agricultural Insurance: Infrastructure for storing, validating and transfer of data securely
Vos et al. (Vos et al. 2017)	Stock/ Land Registration	Fraud, corruption, and lack of trust in classical land registration systems	Smart contracts	A comparison between a classical land registration and blockchain-based land registration system for good governance	Agricultural registration and record keeping: Ownership authentication, enhance trust, and reduce cost by eliminating intermediaries
Cho and Lee (Cho and Lee 2019)	Stock/ Animal Registration	Authenticate animals as specific preregistered entities in various contexts	Nose-print recognition	Nose-print based animal management system for animal registration and authentication	Authentication: Data integrity and accessibility
Mujeye et al. (Mujeye et al. 2023)	Stock/ Farm Overseeing	Failing to meet the quality of service (QoS)	5G and IoT sensors	Local 5G (L5G) network	Data sharing
Lin et al. (Lin et al. 2017)	Stock/ Farm Overseeing	Data security and monitoring data sharing	ICT-based system	A model ICT e-agriculture system with a blockchain infrastructure for water distribution monitoring	Data Integrity and sharing: Verify data integrity
Patil et al. (Patil et al. 2018)	Stock/ Farm Overseeing	Data sharing, irregular satellite monitoring, expensive security methods for energy consumption, and security in IoT	IoT devices	A lightweight blockchain based framework for smart greenhouse farming	Data Integrity and sharing: Data transparency, immutability, scalability, anonymity, distribution, and decentralization
Descovi et al. (Descovi et al. 2021)	Stock/ Monitoring/ Free Range	Exploring the application of blockchain in the health certification process for birds, and traceability of animal sanitary records	N/A	The integration of an animal sanitary control platform (PDSA-RS) with a private blockchain	Data integrity: Simplifying the animal sanitary control of breeding birds, traceability, immutability, transparency, anonymity, and auditability

Table 1 presents a range of blockchain applications within the context of smart agriculture, that address diverse problems, as outlined in the existing literature. The prevailing focus in many smart agriculture studies, as shown in table 1, revolves around data, particularly data integrity and its correlation with quality management standards and certifications. Various projects within the field require data integrity. Moreover, some projects employed secure data sharing underscoring the significance of data integrity as the primary challenge. In this regard, utilizing blockchain technology can potentially address these problems. For instance, a recent integration of blockchain technology within an IoT-based crop prediction system has ensured secure, tamper-resistant storage of sensor data and crop forecasts. This integration utilizes cryptographic techniques to enhance data integrity, decentralize data management, and establish trust among stakeholders (Sizan et al. 2023).

Blockchain's distributed nature ensures high availability, and its consensus algorithms provide immutability of records. Consequently, in literature, many blockchain applications leverage the integrity property of blockchain to provide services such as auditing insurance, bookkeeping, and secure data storage. These services are closely related to quality management, standardization, and certification purposes. There is also a common use in the market for blockchain technology, particularly when high availability is essential. This makes it a versatile tool within the field of smart agriculture.

In a distributed environment, blockchain can play a crucial role in maintaining data through its high availability and integrity verification. It can either serve as the primary repository for data or support any existing information services by ensuring the integrity of the stored data. Additionally, blockchain systems commonly integrate with IoT devices and systems, which generate data that can be automatically recorded in the blockchain. Through the application of blockchain, the integrity of data can be guaranteed, facilitating the automation of day-to-day monitoring operations in smart agriculture. For example, a study aimed at monitoring the impact of fertilizers on agricultural land and related parameters, such as increased temperature, reduced moisture, and light intensities, by recording data in a system using IoT sensors (Rehman et al. 2023).

Effective bookkeeping also plays a significant role in tracking land and animal information. In turn, this aids insurance systems and facilitates insurance audits, serving audit purposes. This process enhances the monitoring standards and certifications of insurance providers. Given the overarching emphasis on data integrity, blockchain technology has become widely adopted for verifying and ensuring the integrity of data across various applications.

Furthermore, it is noteworthy that blockchain is often employed in conjunction with IoT devices and systems to address different problems, automate non-traditional approaches, and devise innovative automated solutions. Many of the data management practices in smart agriculture involve information services, where data is stored in databases and accessible for querying. Blockchain can serve as the underlying database for such information services, and it can be employed to check if the information contained therein is still valid.

While the utilization of smart contracts in smart agriculture remains limited, they have found particular use in insurance and can also be applied to sales within the market. For instance, blockchain-based crop index insurance has been introduced as an innovative solution to overcome the complexities, high costs, and trust issues that plague traditional crop insurance methods. By utilizing blockchain technology, the solution ensures transparency, as every transaction and data exchange is recorded on an immutable ledger. Smart contracts enable autonomous claims processing, significantly reducing the risk of fraud and expediting payouts to farmers. This system also reduces administrative costs by eliminating intermediaries and streamlining processes, making crop insurance more affordable and accessible, especially for farmers in low-income regions (Omar et al. 2023).

Table 1 highlights different areas in agriculture where blockchain technology is applied to address various research problems and improve the overall agricultural processes. In the literature, studies regarding using blockchain in agriculture are divided into three main categories: production, storage, and stock. Blockchain is used in product supply chain as a solution to enhance its functionality, usage, and credibility. It also focuses on improving grain quality management throughout the transportation chain by leveraging blockchain technology and using the GEBN to enhance efficiency and resilience. Blockchain also addresses security concerns in supply chain information exchange and ensures data integrity and authentication, mitigating risks in the agricultural domain.

Studies in product traceability discuss food safety (Chatterjee et al. 2023; Tian 2016; Kumar and Iyengar 2017; Leng et al. 2018; Lin et al. 2018; Lin et al. 2019; Lucena et al. 2018; Mandela et al. 2023; Saberi et al. 2019; Snyder et al. 2017; Tse et al. 2017) and traceability (Ferrández-Pastor et al. 2022; Sezer et al. 2022); Caro et al. 2018; Tian 2016; Figorilli et al. 2018; Kumar and Iyengar 2017; Lin et al. 2018; Lin et al. 2019; Tse et al. 2017) in the agricultural domain. It addresses the problems of tampering with food data (Chatterjee et al. 2023; Mandela et al. 2023); Tian, 2016; Lin et al. 2018; Lin et al. 2019; Lucena et al. 2018) and the limitations of existing traceability systems (Caro et al. 2018; Leng et al. 2018; Tse et al. 2017). The studies also highlight concerns regarding food safety (Chatterjee et al. 2023; Mandela et al. 2023; Tian 2016; Kumar and Iyengar 2017; Leng et al. 2018; Lin et al. 2018; Lin et al. 2019; Lucena et al. 2018; Saberi et al. 2019; Tse et al. 2017) and emphasize that current food safety systems are inadequate to meet the required standards. Blockchain technology is proposed as a solution to enhance traceability in food supply chain, thereby improving food safety and consumer confidence.

Storing agricultural data is also a pressing concern in smart agriculture. The studies focus on some key challenges in the agricultural sector. For example, they address the difficulty of securely storing agricultural and environmental monitoring data (Zhang et al. 2023; Zou et al. 2023; Lin et al. 2017; Pranto et al. 2021; Xie et al. 2017). They also emphasize the movement of vital data (Lin et al. 2017; Pranto et al. 2021; Xie et al. 2017; Zhang et al. 2023; Zou et al. 2023) within the agricultural system. To overcome these challenges, studies (Zhang et al. 2023; Zou et al. 2023; Lin et al. 2017; Pranto et al. 2021; Xie et al. 2017) leverage using blockchain technology that offers a secure and decentralized solution for data storage and management, ensuring the availability and integrity of vital agricultural information.

The literature focuses on improving crop insurance using blockchain technology. Studies (Omar et al. 2023; Bai et al. 2022; Iyer et al. 2021; Jha et al. 2021) in this domain present some approaches such as a decentralized peer-to-peer crop insurance framework (Iyer et al. 2021) to protect farmers' interests and facilitate secure contracts with investors, and a decentralized platform with smart contracts (Jha et al. 2021) to detect fraud and coordinate insurers and farmers efficiently. Blockchain and IoT-based framework was also used in (Bai et al. 2022) to enhance insurance processing, security, and settlement by eliminating human interaction.

This paper covers two main topics in stock registration. Firstly, it discusses the potential applications of blockchain technology in land registration and administration (Anand et al. 2017; Barbieri and Gassen 2017; Vos et al. 2017), highlighting its advantages as well as addressing some concerns about the complexity of integrating it in existing land registry systems. Secondly, the paper presents an animal administration system research that utilizes blockchain for animal identification using nose-print recognition (Cho and Lee 2019), allowing for secure identification, and tracking of animals in various areas such as animal hospitals, pet stores, shelters, and pet insurance.

Blockchain can serve as a useful tool in farm overseeing. For example, Lin et al. (Lin et al. 2017) proposed an e-agriculture system model that utilizes ICT and blockchain for water distribution monitoring. Water quality data is added to the blockchain, ensuring its integrity and availability across all nodes. IoT devices can also be employed as a centrally managed blockchain, providing a more secure and efficient system for remote greenhouse monitoring and automation.

The literature includes some studies related to the application of blockchain technology in monitoring livestock grazing and free range. The AppliFarm platform (ADM 2023) enables digital evidence for animal welfare and livestock grazing through linked tags to track their grazing areas and ensure high-quality grazing for the livestock. Another case study on blockchain's application in the health certification of poultry farms was presented, demonstrating the simplification of animal sanitary control for breeding birds and data storage in the blockchain.

Blockchain technology in smart agriculture faces several technical challenges that need to be addressed to enable its broader adoption. One of the key issues is scalability. As the number of connected IoT devices increases, blockchain networks may struggle to handle the large volume of transactions generated by these devices, which can lead to slower processing times and higher operational costs. To address scalability and energy consumption challenges, alternative consensus mechanisms like Proof of Stake (PoS), used by Ethereum 2.0 and Cardano, provide energy efficiency while maintaining robust security. Additionally, Delegated Proof of Stake (DPoS), employed by platforms such as EOS and Tron, further improves scalability but comes with the trade-off of increased centralization (Alkhodair et al. 2023).

Another significant challenge is data privacy. Public blockchain platforms are transparent by design, which could expose sensitive agricultural data to unauthorized parties. To overcome this, permissioned blockchains can be implemented to restrict access, ensuring that only authorized participants can access certain data. Furthermore, techniques like Zero-Knowledge Proofs (ZKPs) (Zhang et al. 2023) can allow data to be verified without revealing the underlying information, ensuring privacy while maintaining transparency.

Another major limitation is the absence of standardized regulations and international frameworks, which restrict interoperability and delay widespread implementation. Connectivity issues in rural areas further complicate participation, as blockchain networks require reliable internet access. Additionally, the technology demands substantial IoT infrastructure to ensure accurate and trustworthy data input, creating logistical and financial hurdles. Uncertainty regarding the legal interpretation of smart contracts and governance frameworks adds to the complexity, posing legal and operational risks. Overcoming these regulatory, infrastructural, and accessibility challenges is essential for blockchain to achieve its transformative potential in enhancing transparency, efficiency, and sustainability in the agricultural sector (AGDAILY 2024).

Different blockchain systems may use incompatible data formats or communication protocols, making it difficult to integrate them with existing agricultural systems and it can arise communication issues. The development of universal standards for data exchange and protocol integration would facilitate smoother interoperability and greater collaboration across platforms, leading to more efficient blockchain-based solutions in agriculture. Addressing these technical limitations will be crucial in unlocking the full potential of blockchain to improve transparency, efficiency, and security in the agriculture sector.

Although there are significant studies have examined various aspects of smart agriculture, researchers are increasingly directing their focus toward the supply chain (Ahamed and Vignesh 2022; Ashfaq 2022; Chatterjee et al. 2023; Haji et al. 2022; Kumar and Dwivedi 2023; Mandela et al. 2023), encompassing the entirety of activities from crop cultivation to consumer. This shift is occurring because individuals are increasingly recognizing the importance of effectively managing this process to ensure that farming operations are conducted efficiently and with traceability. Delving into the supply chain, researchers aim to identify strategies for resource optimization, product enhancement, and waste reduction in agricultural operations. Additionally, the increasing consumer consciousness regarding food provenance and production methods underscores the need to ensure transparency within the supply chain. Technologies like blockchain help achieve this goal by enabling the enhanced tracking of food origins and the handling processes. Consequently, the exploration of the relationship between smart agriculture and the supply chain is emerging as a significant area of research, which will yield substantial improvements in agricultural practices for broader societal benefit.

Despite the numerous benefits of using blockchain in smart agriculture, there are still several open questions and areas that require further research. For instance, using blockchain to track soil quality metrics such as nutrient levels, pH, and organic matter content. This data could then be used to optimize soil health and productivity and identify areas requiring specific treatments. In smart agriculture, Blockchain technology can enable several transformative capabilities. For example, the creation of decentralized markets, and fostering direct connections between farmers and buyers. Additionally, blockchain can facilitate the development of auditing systems to monitor and support environmentally friendly farming practices. By utilizing smart contracts, the use of intermediaries can be minimized, which will lead to reduced food prices and improved efficiency in the agricultural supply chain. Finally, blockchain could be used to track research data, funding, and collaborations in agricultural research, enabling greater sharing and collaboration among researchers.

Feature studies on blockchain applications in agriculture should focus on several emerging areas. Developing standardized frameworks is essential to enable seamless integration of blockchain with IoT and AI technologies, fostering interoperability across industries. Studies are needed to assess the economic and operational viability of blockchain solutions, particularly in resource-constrained farming environments. Exploring hybrid blockchain models that combine public and private chains could help achieve a balance between transparency and scalability. Furthermore, addressing ethical considerations and socio-economic impacts is critical to ensure equitable benefits for smallholder farmers and reduce potential disparities. Finally, localized investigations should examine how blockchain can address region-specific challenges, such as enhancing drought resilience in arid regions or implementing disease tracking systems in livestock farming, tailoring solutions to the unique needs of different agricultural contexts.

In conclusion, this paper has highlighted the numerous applications of blockchain technology in smart agriculture, including product supply chain management, storage, farm, and stock management. By leveraging the power of blockchain, we can create a more transparent, sustainable, and equitable food system for all. However, further research is required to address open questions and areas to ensure the successful integration of blockchain into the agriculture industry. Overall, this paper contributes to the ongoing discussion on the potential of blockchain in smart agriculture and highlights the need for further research to realize its full potential.

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Disclaimer: The entirety of the ideas and contributions presented are the authors' original work. Nonetheless, we incorporated a Large Language Model (LLM) to improve the clarity and readability of the text. It should be noted that despite utilizing the LLM for language enhancement, the work remains solely our own.

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