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# A Survey of Blockchain Applications for Management in Agriculture and Livestock Internet of Things

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**Abstract:** In the area of agriculture and livestock management, the integration of the Internet of Things (IoT) has emerged as a groundbreaking strategy to enhance operational efficiency and advance intelligent process management. However, this sector faces significant challenges, including ambiguity in product origins and limited regulatory oversight of IoT devices. This paper explores the innovative integration of blockchain technology within the agricultural and livestock IoT, highlighting how this convergence significantly enhances operational security and transparency. We provide an in-depth review of the latest applications and advancements of blockchain in these domains, offering a comprehensive analysis of the current state of technology and its implications. Furthermore, this paper discusses the potential future development trajectories in agricultural and livestock IoT, emphasizing blockchain's role in addressing current challenges and shaping future innovations. The findings suggest that blockchain technology not only improves data security and trustworthiness but also opens new avenues for efficient and transparent management in agriculture and animal husbandry.

**Keywords:** Internet of Things; blockchain; livestock management; agricultural supply chain; privacy protection; data encryption

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## 1. Introduction

In the contemporary global landscape, agriculture and livestock play an essential role in fulfilling the escalating demand for food. The United Nations Food and Agriculture Organization projects to sustain the global population by 2050 for the necessity of a 60% increase in food production [1]. This imperative highlights the critical challenge of securing a stable global food supply, a challenge that the integration of Internet of Things (IoT) technology into agriculture and livestock endeavors aims to mitigate by offering a plethora of innovative solutions.

In recent years, the application of IoT technology in agriculture and livestock has been receiving increasing attention [2]. IoT represents a network architecture that enables seamless connectivity and communication among various objects and devices, thus enabling the efficient sharing of data from the natural world. This system, which incorporates embedded software, batteries, and sensors, relies on both wireless and wired microcontrollers to provide cost-effective solutions [3]. Within the domain of agriculture and livestock management, IoT technology serves a specialized role connecting fields, pastures, warehouses, and farms to create a network that enables sophisticated monitoring and management of crops and livestock. Researchers have categorized agricultural IoT into seven distinct classes: Smart Monitoring, Smart Water Management, Agrochemical Applications, Crop Disease Management, Smart Harvesting, supply chain management, and Smart Agricultural Practices [4]. These technologies offer real-time insights into crop management and the surrounding environment, facilitating data-driven decisions for precision agriculture, such as optimal irrigation and fertilization strategies [5]. Similarly, in livestock management, the integration of IoT and AI technologies supports automated health monitoring and identification, enhancing overall breeding [6].

Although IoT technology brings many benefits to agriculture and livestock, including improved production efficiency and quality, it also faces many challenges in its implementation. These challenges encompass data security risks, transparency deficiencies, regulatory complexities, and the high costs and resource requirements for advanced data analysis. Addressing these challenges requires us to adopt additional strategies to cope, such as blockchain technology.

Blockchain technology, first introduced in 2008 as the foundation of Bitcoin by Satoshi Nakamoto, operates as a decentralized digital currency system that functions independently of major financial institutions and enables direct transactions among users. Blockchain technology centers around a tamper-proof, decentralized, public distributed ledger that consists of blocks arranged chronologically, providing strong data security and integrity. In the agricultural and livestock IoT, significant benefits arise from utilizing blockchain technology, particularly in tackling data security, transparency, and credibility issues due to increased data volumes and the involvement of multiple stakeholders. Firstly, as a distributed storage structure, blockchain reduces the pressure of traditional centralized data storage, enhancing data availability and persistence. Secondly, it ensures the accuracy and security of data, guaranteeing that once recorded, the data cannot be altered or deleted. Additionally, blockchain demonstrates tremendous potential in supply chain traceability and verification, enabling full-track tracing from production to consumers and enhancing the traceability and trustworthiness of agricultural products [7–9]. Finally, operations can be conducted through smart contracts and automated programs that automatically carry out relevant operations once predetermined conditions are satisfied [10].

While blockchain technology offers decentralized advantages such as transparency and trust, there are scenarios in agriculture and livestock management where centralized systems excel. These include situations requiring rapid decision-making, unified command, or efficient resource allocation, such as food safety management, disease outbreak control, or government subsidy distribution. For instance, in the management of specific agricultural products subject to strict government oversight, centralized systems may already offer efficient and reliable solutions. Introducing blockchain in such contexts could lead to unnecessary complexity and resource allocation challenges. Future research should focus on delineating the specific conditions under which blockchain technology is either beneficial or redundant in agricultural and livestock systems.

1. Providing a Comprehensive Background for Novices

Before delving into the latest research findings, this paper systematically introduces the foundational concepts of IoT applications in agriculture and livestock, as well as blockchain technology. In contrast to existing overviews that primarily address either IoT or blockchain in isolation, our approach integrates insights from multiple recent studies to underscore how prior work has laid the groundwork for linking these two domains. This dual overview enables readers—especially those new to the field—to quickly understand how IoT and blockchain function within agricultural and livestock management. Consequently, our work serves as an accessible starting point for researchers aiming to explore these areas in depth.

2. Highlighting the Challenges and Motivations for Integrating Blockchain into Agricultural and Livestock IoT

We thoroughly examine the current challenges in agricultural and livestock IoT, including data security vulnerabilities, transparency issues, and reliability concerns. Building on the findings from prior research that has identified these pain points in various IoT-driven agri-food supply chains, we correlate them with the inherent attributes of blockchain (such as immutability, decentralized data storage, and trust enhancement). Therefore, we illuminate the motivations and advantages of combining blockchain with IoT in this domain. This explicit linkage to earlier studies clarifies how the recognized blockchain features can address the specific gaps highlighted by previous authors, thereby explaining how blockchain can specifically tackle core pain points of agriculture and livestock management.

3. Presenting a Novel Classification Scheme for Blockchain Applications in Agriculture and Livestock IoT

Unlike most existing review articles that primarily focus on broad integration or a single aspect (e.g., traceability), we draw upon multiple recent investigations (published within the past 3–5 years) to formulate a more comprehensive classification strategy. Through this in-depth analysis of recent studies, we categorize the applications of blockchain in agricultural and livestock IoT into four key themes—data storage and management, supply chain traceability, smart contract implementation, and security and trust assurance. By consolidating the diverse findings of these studies, we extend the existing classifications and highlight the multifaceted roles of blockchain in meeting the varied requirements of modern agriculture and livestock systems. This approach provides researchers and practitioners with clear directions for future exploration and application.

4. Analyzing Existing Research Gaps and Proposing Future Directions

Based on our extensive review, we summarize the critical open issues—ranging from regulatory challenges to system scalability—and discuss how they may affect the successful integration of blockchain in agriculture and livestock IoT. By synthesizing the unresolved topics raised in earlier works, such as the lack of standardized protocols or difficulties in large-scale implementation, we propose promising future research paths, including the design of domain-specific consensus mechanisms, the synergy between centralized and decentralized systems, and the potential coupling of AI-driven analytics with blockchain. These recommendations directly build on the shortcomings identified in prior research and aim to guide future innovation and sustainable development of agricultural and livestock IoT systems.

By combining foundational explanations with an in-depth classification of the latest research, our work not only clarifies why blockchain should be integrated into the agricultural and livestock IoT but also demonstrates how the existing literature directly informs and validates our proposed strategies. This dual focus differentiates our article from existing reviews and provides a more comprehensive resource for researchers and practitioners seeking to advance the application of blockchain in agriculture and livestock.

Section 2 of the paper delves into the concepts of smart agriculture and animal husbandry, along with the technical specifics of blockchain. Section 3 focuses on the challenges encountered in the agricultural and livestock IoT, highlighting the crucial role of blockchain in overcoming these issues. Section 4 delves into a detailed analysis of blockchain applications in this realm. In Section 5, we explore future research opportunities in integrating blockchain with agriculture and pastoral IoT. This paper's structure is depicted in Figure 1.

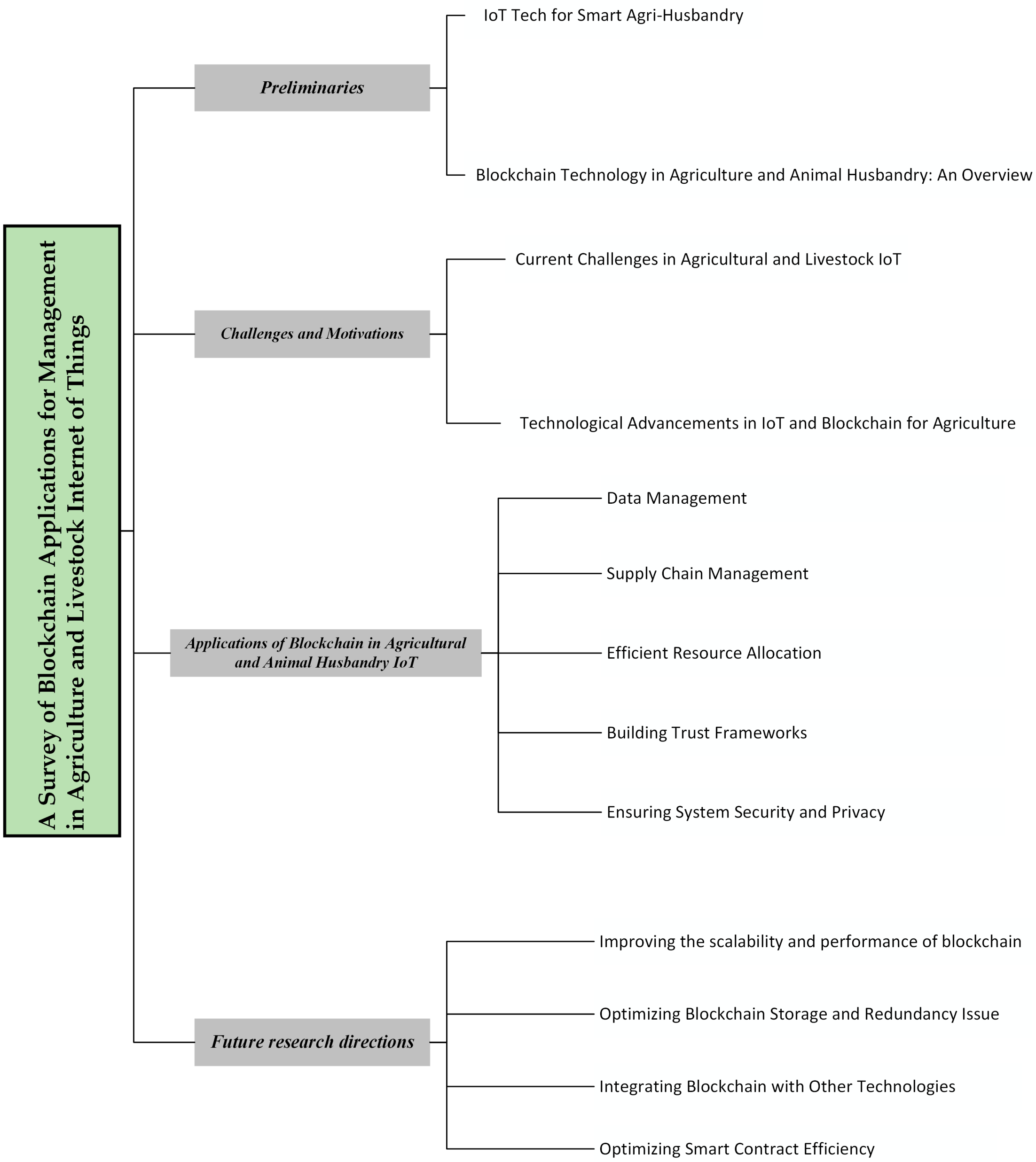


**Figure 1.** Organization of this paper.

## 2. Preliminaries

In this study, multiple authoritative scientific databases were chosen during the literature review process to ensure the comprehensiveness and quality of the selected literature. The databases used include Web of Science, IEEE Xplore, MDPI, Engineering Index (Ei), and Science Direct. Regarding the literature selection, studies published from 2019 to 2023 on the applications of blockchain and the Internet of Things (IoT) in agriculture and animal husbandry were included. Keywords such as “blockchain”, “Internet of Things”, “agriculture”, and “animal husbandry” were employed to optimize the search results. The inclusion criteria focused on peer-reviewed journal articles and conference papers to ensure the scientific rigor and authority of the research, while the exclusion criteria removed literature that was not directly relevant to the research topic or of insufficient quality, such as non-peer-reviewed preprints. A preliminary search was conducted in the selected databases, followed by screening based on the defined selection criteria.

This section succinctly presents the core technologies and application areas of the agricultural and pastoral IoT, as well as the key technologies of blockchain. In addition, we also explore how these two technologies can be combined and applied in the agricultural and pastoral IoT.

### 2.1. IoT Technology and Smart Agriculture and Animal Husbandry

The Internet of Things (IoT) refers to an interconnected ecosystem of everyday objects that gather and exchange data over a network. These devices—ranging from household appliances to industrial machinery—are equipped with embedded sensors, actuators, and dedicated communication hardware, enabling them to sense, interact, and transmit information. Today, the IoT is being deployed across nearly every industry and scenario, including smart homes [11], smart buildings [12], the Industrial Internet of Things [13], smart cities [14], intelligent transportation [15], and smart agriculture [16]. The emergence of IoT technology has brought unprecedented opportunities to various industries, especially in the field of agriculture [17,18]. The following is an overview of some basic components of IoT and how they work:

Below is a summary of the fundamental components of the IoT and an explanation of their functionality:

Key Components of IoT:

1. IoT devices: These are physical objects capable of connecting to and communicating over the internet. They range from everyday household appliances, like refrigerators and washing machines, to more sophisticated industrial tools, such as robots and drones [19].
2. Sensors: Integral to the IoT, sensors are tasked with collecting diverse types of data, encompassing aspects like temperature, humidity, location, and motion. The data they gather lay the groundwork for the IoT system's environmental responsiveness [20].
3. Network connectivity: Network connectivity, encompassing both wireless (Wi-Fi, Bluetooth, 5G) and wired (Ethernet) connections, is vital for transferring data from devices to processing centers or other interconnected devices. These connections ensure the swift and secure transmission of data [21].
4. Data processing: Post-collection, the data undergo processing and analysis, which may occur on local smart devices, edge computing devices, or in cloud-based systems. This stage involves data cleansing, categorization, analysis, and decision-making processes [22–24].

These components collectively enable the IoT to amalgamate data collection, real-time analysis, and automated response, facilitating intelligent and autonomous device operation. This integration boosts efficiency, reduces waste, and strengthens system security.

Smart agriculture leverages IoT, big data, AI, and various modern information technologies to achieve intelligent management and precision operations, aiming to enhance efficiency and improve the quality of agricultural outputs within the framework of modern agricultural practices [25,26].

The application of IoT technologies in agriculture has become increasingly widespread, with numerous successful examples serving as valuable references. For instance, in precision agriculture, IoT-based sensor networks are employed to monitor and collect real-time data on various environmental parameters, such as soil moisture, air temperature, humidity, geographic location, and crop growth status [27,28]. These data are then transmitted to cloud platforms or local servers for analysis and processing, providing actionable insights for informed decision-making. By utilizing these accurate, real-time data streams, farmers and agricultural managers can dynamically adjust irrigation and fertilization strategies, monitor and prevent pest infestations, and even remotely control irrigation systems or greenhouse ventilation devices via automated systems [29,30].

Beyond precision agriculture, IoT technologies are extensively applied in diverse sectors such as aquaculture, forestry, and vertical farming. In aquaculture, sensors monitor water quality parameters like pH, dissolved oxygen, and temperature to ensure optimal conditions for fish growth [31]. Forestry applications include IoT devices that track forest health, detect early signs of wildfires, and manage timber resources efficiently [32]. One study demonstrates that using an MQTT-based publish architecture for fire detection in smart agriculture significantly enhances real-time responsiveness and resource efficiency [33]. In urban vertical farming, IoT systems control climate conditions, nutrient delivery, and pest management to maximize yield in limited spaces [34]. Additionally, precision livestock farming utilizes IoT sensors to monitor animal health, behavior, and environmental conditions, enhancing overall livestock management and welfare [35].

The geographical deployment of IoT sensors in agriculture showcases their adaptability and global significance. In Africa, smallholder farmers employ low-cost soil moisture sensors integrated with solar-powered communication modules to optimize irrigation practices, thereby improving crop yields in water-scarce regions [36,37]. The Americas sees the use of UAV-based imaging sensors in large-scale coffee plantations to detect crop stress and pest infestations early, enabling timely interventions and reducing crop losses [38,39]. In Southeast Asia, IoT sensors in aquaculture systems monitor water quality to maintain ideal rearing conditions for fish, enhancing productivity and sustainability [40]. In Europe, advanced IoT technologies such as sensor-based data analysis and autonomous bots are utilized in greenhouse operations to optimize control and monitoring [41]. Meanwhile, in Asia, smart irrigation systems in litchi orchards utilize real-time data to manage water resources precisely, promoting sustainable agriculture and reducing environmental impact [42].

Moreover, IoT technologies enable higher levels of integration and optimization in agricultural operations. By deploying diverse sensors across farms and integrating GPS positioning with data visualization platforms, managers can gain a comprehensive view of environmental conditions and crop health across different regions of the farm. This facilitates precise production planning, reduces labor costs and resource waste, and ultimately boosts both yield and quality [43]. Additionally, some farms utilize drones or robots equipped with image-capturing sensors to transmit real-time imagery, enabling the monitoring of large-scale crop health and growth dynamics while supporting targeted agricultural interventions [44,45].

Similarly, the use of IoT technology in animal husbandry can bring about revolutionary changes. Smart animal husbandry integrates advanced technologies for real-time monitoring and analysis during the livestock breeding process in order to achieve the automation of breeding management of the innovative livestock farming model [46].

In smart animal husbandry, by deploying various sensors in the pastures, ranch owners can monitor key indicators of livestock, such as health status, range of activity, feed consumption, and growth conditions in real-time [47]. For example, by monitoring the body temperature and activity data of livestock, health issues can be identified promptly, allowing for early treatment and reducing the spread of diseases and losses [48]. Moreover, by analyzing big data, ranch owners can optimize feed ratios and improve feed utilization, thereby reducing costs and enhancing production efficiency [49].

Smart animal husbandry can also help ranch owners better manage ranch resources, such as pastures, water sources, and feed storage. Through IoT technology, ranch owners can understand the growth condition of pastures, the usage of water sources, and the storage of feed in real-time, thus making more rational management decisions [50].

Significantly, comprehensive monitoring of livestock can ensure that animals grow in a healthy and safe environment, thereby enhancing the quality of livestock products. Concurrently, by employing blockchain technology, complete traceability information on livestock can be provided to consumers, enhancing their trust in livestock products. Figure 2 illustrates the overall architecture of smart agriculture and animal husbandry, where each element collaborates to form an efficient IoT ecosystem. This is a conceptual example we proposed to demonstrate the integration of IoT technologies in agricultural and livestock management.

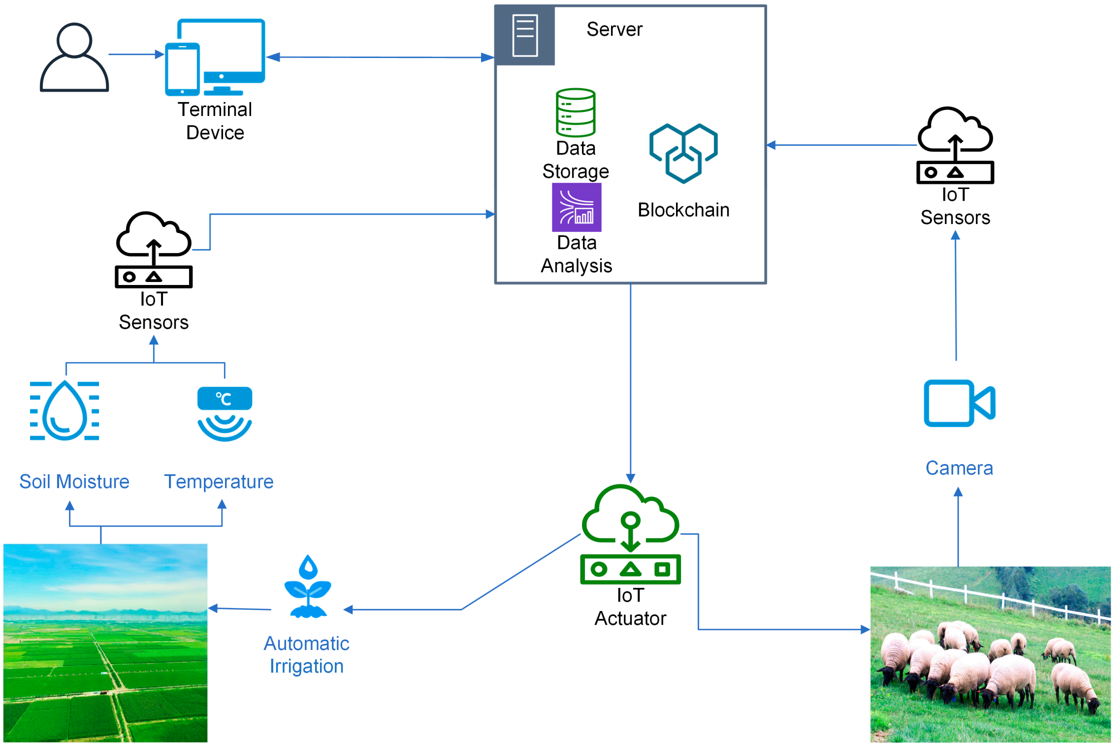


**Figure 2.** Smart agriculture and animal husbandry.

Below is a breakdown of the main elements, the meaning of each arrow, and the role of underlying protocols:

(1) Data Collection and Transmission

Deployed in farmland to measure soil moisture, temperature, and other environmental parameters and in livestock areas to monitor animal health, activity, and environmental conditions. These sensors utilize wireless protocols such as Wi-Fi to transmit real-time data efficiently.

Arrows from IoT sensors to server: These arrows represent the continuous flow of sensor data (e.g., moisture levels, temperature readings, livestock health metrics) being transmitted wirelessly to the central server for storage and subsequent analysis. The directionality of the arrows indicates the unidirectional flow from data collection points to the processing unit.

(2) Server (Center)

Data storage and analysis: The server is the system's core, hosting data repositories and analytics modules. Sensor data, camera feeds, and user inputs are stored here for further processing.

Blockchain module (within the server): Embedded within the server architecture, the blockchain module ensures data immutability, traceability, and tamper-proof transactions. This integration leverages smart contracts and consensus mechanisms (such as Proof of Stake or Practical Byzantine Fault Tolerance) tailored specifically for agricultural use cases. The blockchain layer records critical transactions and data exchanges, enhancing the system's security and trustworthiness.

(3) User Interaction

Terminal device (top left): Farmers, technicians, and other stakeholders interact with the system through smartphones, tablets, or computers. These devices access real-time insights via web or mobile applications, utilizing protocols like HTTP and MQTT to facilitate seamless communication with the server.

Arrow from terminal device to server: This arrow denotes the flow of user commands or configuration updates sent from the terminal devices to the server. Examples include adjusting irrigation schedules or setting temperature thresholds, enabling users to manage and control the agricultural environment remotely.

Arrow from server to terminal device: Representing the server's responses, alerts, and analytical results, this arrow illustrates how processed data and notifications are communicated back to the users. This bidirectional flow allows users to monitor farmland and livestock in real-time and make informed decisions based on the server's analysis.

(4) Actuation and Control

Actuators receive commands from the server to perform physical actions, such as activating irrigation pumps, adjusting greenhouse ventilation, or dispensing feed for livestock. These devices execute automated or semi-automated responses to environmental changes.

Arrows between IoT actuator and farmland/livestock: These arrows reflect the actuator's dual role in both crop cultivation and animal husbandry. For crop cultivation, actuators manage automatic irrigation and nutrient delivery systems. In animal husbandry, they regulate feeding systems and temperature control in barns, ensuring optimal conditions for livestock health and productivity.

Arrows from server to IoT actuators:

These indicate the flow of control commands from the server to IoT actuators. For instance, based on the analyzed soil moisture and temperature data, the server sends commands to activate irrigation pumps or adjust greenhouse ventilation systems.

(5) Camera Monitoring

Camera (right center): cameras installed in livestock areas capture real-time video or images, providing visual data on animal behavior and health. These multimedia data are sent to the server for further analysis, including AI-driven health checks and behavior monitoring.

The arrow from camera to server: This arrow indicates the transmission of multimedia data from the cameras to the server. The integration of visual data with other sensor information offers comprehensive situational awareness, enabling early detection of anomalies and timely interventions.

(6) System Outcomes

Automatic irrigation: Leveraging soil moisture data and preset thresholds stored within the server's analytics modules, the system can autonomously trigger irrigation pumps. This optimizes water usage, ensuring that crops receive the necessary hydration without wastage.

Livestock management: By analyzing data from sensors and camera feeds, the server can detect anomalies such as abrupt temperature changes or reduced animal activity. These detections prompt alerts to users or direct commands to actuators, facilitating prompt corrective actions to maintain livestock health and welfare.

Through these interconnected modules and clear data flows, the proposed architecture demonstrates how IoT devices, analytics, and blockchain integration can enhance transparency, trust, and efficiency in both agriculture and animal husbandry.

### 2.2. Blockchain Technology in Agriculture and Animal Husbandry: An Overview

Blockchain is an automated system programmed to activate and perform specific functions when predefined criteria are met. This functionality enables the automated and transparent execution of complex business processes on the blockchain, presenting immense potential value across various sectors. In this way, blockchain can automatically execute transaction information storage and operations under specific conditions, performing certain actions automatically (such as feeding or irrigation) when conditions like time, temperature, or humidity are met [51]. In supply chain tracking, blockchain can also store all transaction information through smart contracts [52]. Despite its strengths, blockchain technology confronts certain challenges. With the escalation in data volume on the blockchain, processing speed and storage demands increase, potentially affecting overall system efficiency [53]. Moreover, while blockchain is generally secure, it is not impervious to threats, including vulnerabilities like the 51% attack [54], contract vulnerabilities, and scalability issues. Additional concerns include interoperability, privacy exposure, and evolving regulatory landscapes, underscoring the need for ongoing advancements and solutions.

Blockchain technology represents a distinctive database model that organizes data into linked blocks, creating a chain-like formation. Each block comprises a collection of transaction data, a timestamp, and cryptographic hashes of its preceding block, providing secure and unalterable records. In the blockchain, a series of blocks are linked together through encryption algorithms and are distributed and stored in a decentralized P2P network, ensuring the data's immutability and transparent sharing. With a consensus mechanism in place, potential data modifications can be agreed upon by the majority of network participants, thus maintaining a balance between immutability and adaptability. Additionally, the use of cryptographic technology secures data, and smart contracts automate contract conditions. Blockchain technology is categorized based on application scenarios and access permissions, showcasing its adaptability to various fields.

Blockchain technology, based on different application scenarios and access permissions, is divided into the following categories:

Public Blockchains [55]:

Public blockchains are open blockchain networks that are accessible to everyone. Anyone can participate in the operation of the network, send and verify transactions, or participate in the creation of new blocks.

Private Blockchains [56]:

Private chains are controlled networks that only allow specific individuals or organizations to verify transactions and create blocks. These networks are typically used within enterprises, offering faster transaction speeds and better privacy protection.

Consortium Blockchain [57]:

As a variant of a private blockchain, consortium blockchain shows significant differences from traditional private chains. Private chains primarily serve the exclusive needs of a single company, whereas consortium blockchain focuses on collaboration between multiple companies or organizations, aiming to provide cross-industry services.

Hybrid Blockchain [58]:

Operating in a controlled environment akin to a private blockchain, the hybrid blockchain allows certain data and operations to be accessible by the public, aiming to merge the benefits of different blockchain types to offer solutions that ensure privacy protection while also providing transparency.

2.2.1. Block and Agricultural and Animal Husbandry Data Storage

Blocks in a blockchain are essential for securely storing agricultural and livestock-related data in an immutable manner. For instance, in a crop supply chain, each block can record critical information such as harvest dates, storage conditions, and transportation logs. Similarly, in animal husbandry, blocks can document the vaccination history, health status, and feeding records of livestock, ensuring that these data are both traceable and tamper-proof. This capability fosters transparency and builds consumer trust in agricultural and livestock products.

The integration of blockchain and IoT technologies in animal husbandry significantly enhances data reliability, traceability, and transparency across the livestock management ecosystem. Blockchain systems ensure the authenticity of vaccination histories, health records, and feeding patterns, creating tamper-proof, immutable ledgers that streamline livestock monitoring. For instance, a livestock shed regulatory platform proposed by Shen et al. uses blockchain and IoT to automate livestock insurance processes while ensuring real-time environmental data monitoring, reducing operational costs, and improving efficiency [59]. Similarly, a blockchain-supported framework demonstrates high efficiency in livestock behavior monitoring and supply chain transparency, bringing significant benefits to producers, regulators, and consumers [60].

Moreover, blockchain applications extend to unmanned aerial vehicle data collection for livestock, ensuring secure monitoring and effective integration of decentralized systems, as proposed by Ortega et al. [61]. Such advancements not only foster consumer trust but also streamline compliance with animal welfare and food safety regulations, as demonstrated by prototypes like the Hyperledger-based system for animal surveillance [62].

A blockchain is composed of blocks, each divided into a header and a body. The body contains verified transaction data, such as digital currency transfers or smart contract executions, while the header includes specific details such as the hash of the previous block, a nonce, difficulty level, and the Merkle root value. These blocks are cryptographically linked to form an ever-growing chain, ensuring data security and immutability. This distributed and decentralized structure provides unique advantages, including decentralization, transparency, and security. Figure 3 illustrates the structure of a single block, and Figure 4 depicts the chain-like formation of a blockchain.

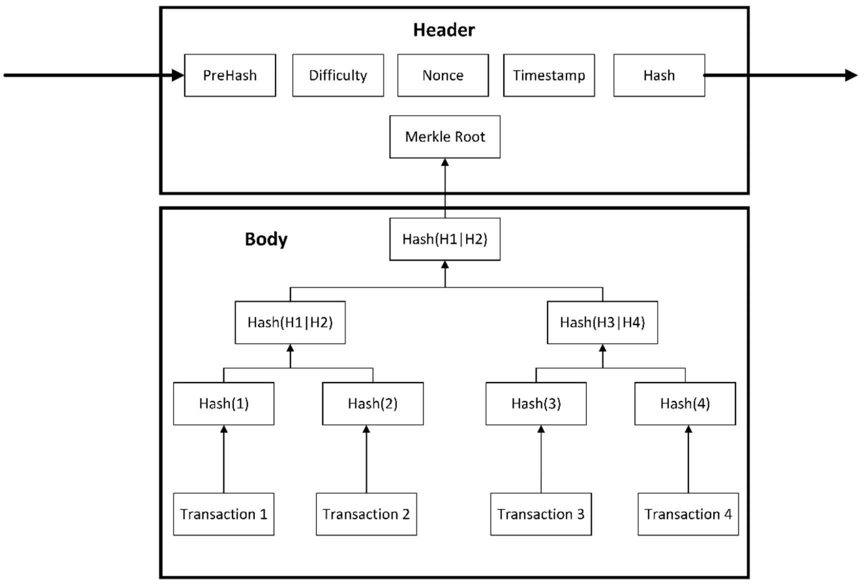


**Figure 3.** Structure diagram of the block.

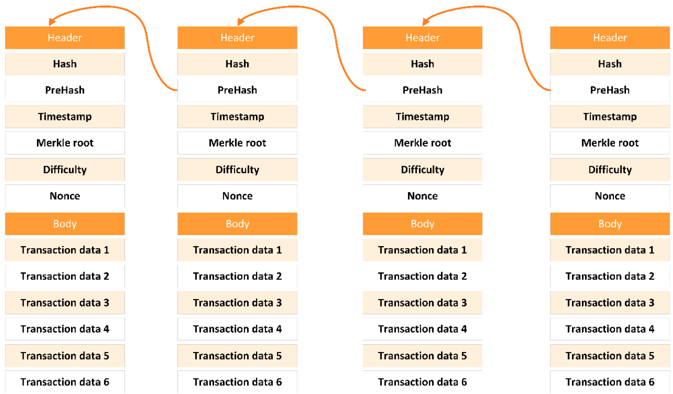


**Figure 4.** Blockchain chain-like structure.

2.2.2. Smart Contracts for Agricultural and Animal Husbandry Automation

Smart contracts, composed of programmer-written code, establish rules and conditions that automatically execute contract terms once these conditions are met. Operating within the blockchain's decentralized environment, they guarantee execution transparency and immutability.

Smart contracts play a crucial role in automating agricultural and livestock processes by executing predefined rules once certain conditions—often captured by IoT devices—are met. For instance, in a dairy farm, a smart contract can automatically settle payments to milk suppliers based on real-time volume measurements collected via sensors, ensuring prompt and accurate compensation without manual intervention. In crop farming, a smart contract might trigger irrigation systems the moment soil moisture levels drop below a predefined threshold, thus optimizing water usage and reducing labor costs. Beyond these fundamental applications, some large-scale operations integrate weather data into their smart contracts to adjust feeding schedules or activate greenhouse controls in anticipation of rainfall or extreme temperatures, effectively protecting both crops and livestock. Similarly, government-led pilot projects have explored smart-contract-based subsidies, where funds are released only after digital monitoring confirms that specific sustainability or productivity benchmarks have been met. By minimizing human errors and administrative delays, these automated processes streamline daily operations and foster trust among farmers, suppliers, and regulators, who can transparently review contract terms and outcomes on the blockchain. As a result, smart contracts serve as a powerful catalyst for data-driven decision-making in modern agriculture and livestock management, paving the way for more resilient and sustainable farming ecosystems.

Blocks in a blockchain are essential for securely storing agricultural and livestock-related data in an immutable manner. By linking each block to its predecessor through cryptographic hashes, the blockchain prevents any data within a previous block from being altered without immediately revealing tampering. In a crop supply chain, for instance, each block could record critical information such as harvest dates, storage conditions, transportation logs, and even quality inspection results. If a product is flagged for substandard quality, stakeholders can quickly trace back through the chain of blocks to identify where and when the problem occurred—whether it was in the harvesting process, cold storage, or during transportation. This not only expedites recall procedures when necessary but also helps enforce accountability among different participants in the supply chain.

Smart contracts are meticulously crafted programs by software developers tailored to operate on blockchain platforms, exemplified by the use of Ethereum's Solidity language [63]. The consensus algorithm in blockchain networks ensures transactional consensus among all participants, thus maintaining network consistency and security [64]. They incorporate precise operational logic and establish various trigger conditions and execution protocols. For instance, a smart contract might stipulate that a financial transfer between accounts only occurs in response to specific events, such as a predetermined date or the reception of particular data. The inherent automation of smart contracts obviates the dependence on conventional intermediaries, like lawyers or banks, substantially reducing transactional time costs and markedly diminishing risks associated with human error or fraudulent activities.

Functioning as a decentralized distributed ledger, blockchain allows smart contracts to operate autonomously in a central authority-free environment, executed and verified independently by numerous nodes. Contract execution outcomes are permanently recorded on the blockchain, accessible for public verification, thus ensuring utmost transparency and security

#### 2.2.3. Consensus Mechanisms for Agricultural and Animal Husbandry Networks

Blockchain consensus mechanisms are frameworks devised to secure universal concord among all network participants regarding transactions and the blockchain's collective status. These algorithms are pivotal to blockchain technology, addressing critical issues like the double-spending problem (where the same digital currency could be spent twice) and ensuring data consistency across the decentralized network.

Consensus algorithms ensure data integrity and consistency in distributed agricultural networks. For instance, in a network of smallholder farms, a Proof of Stake (PoS) mechanism can be used to validate crop growth data reported by various sensors, preventing any false data from entering the system. Similarly, in livestock management, a consensus algorithm can confirm accurate tracking of cattle movement across distributed nodes, such as those used in traceability systems for organic certification.

Various blockchain platforms employ different consensus algorithms, each with unique features and mechanisms.

Proof of Work (PoW) [65,66]: Employed by Bitcoin and various other blockchain networks, PoW mandates that network nodes (miners) authenticate blocks through the resolution of intricate cryptographic challenges. The first miner to solve the challenge earns, necessitating extensive computational power and electricity.

Proof of Stake (PoS) [67]: A node's eligibility to append new blocks is determined by its stake, often quantified by the volume of cryptocurrency it holds, in the PoS mechanism. Nodes with greater cryptocurrency holdings have a higher probability of validating transactions and creating blocks. PoS surpasses PoW by eliminating the need for extensive computational tasks, thereby enhancing energy efficiency.

Delegated Proof of Stake (DPoS) [68]: In this consensus algorithm, cryptocurrency stakeholders vote to elect a select group of delegates or witnesses who are tasked with the validation of transactions and the creation of new blocks. This system enables quicker transaction confirmations and can process a larger volume of transactions, though it may lead to power centralization within the network.

Practical Byzantine Fault Tolerance (PBFT) [69]: Designed to maintain system functionality even when some nodes fail (including malicious ones), PBFT reaches consensus through multiple rounds of communication among nodes. While effective in small to medium networks, PBFT's communication demands escalate with network growth, impacting scalability.

Proof of Authority (PoA) [70,71]: PoA entrusts transaction validation and block creation to a small number of trusted, publicly known, and verifiable validators. This system allows for rapid transaction processing and lower energy use but may compromise some decentralization due to its reliance on a limited number of validators.

The blockchain field is marked by a multitude of consensus algorithm variations, each addressing specific challenges like energy efficiency, transaction speed, security, decentralization, and scalability. These adaptations are tailored to the unique requirements of different networks, striving for a balance between speed, security, decentralization, and other critical factors. As blockchain technology evolves, new and refined consensus algorithms are anticipated to emerge, further enhancing the capabilities and applications of this transformative technology.

#### 2.2.4. Cryptographic Security in Agricultural and Animal Husbandry Applications

When mentioning blockchain, many people first think of cryptocurrencies, which fundamentally rely on cryptographic algorithms, while blockchain technology utilizes various cryptographic techniques for network security and functionality. In blockchain, cryptography is also used to achieve three main security objectives: confidentiality (hiding information through encryption techniques), integrity (using cryptographic hash functions to prevent illegal modifications), and availability (ensuring information is always accessible to intended users) [72]. The cryptographic technology foundational to blockchain is crucial for the privacy and integrity of data, particularly in the agricultural and pastoral IoT, where this encryption technology safeguards sensitive information collected by sensors on crop or animal health from unauthorized access [73].

Cryptographic algorithms ensure the security and confidentiality of sensitive agricultural and livestock data. For instance, in agricultural e-commerce platforms, encryption can protect transaction details between farmers and buyers. In animal husbandry, cryptographic methods can secure data related to genetic records or health tracking of high-value livestock, preventing unauthorized access or tampering. This ensures the integrity of critical agricultural information in digital ecosystems.

Below are some key cryptographic technologies in blockchain technology:

Hash functions [74]: Hash functions in blockchain technology are crucial for ensuring data integrity and security by generating a unique identifier or hash value. This mechanism enables the blockchain to effectively ascertain if any data have been altered.

Public key cryptography [75]: Within blockchain environments, the method uses a pair of keys for asymmetric encryption: a public key, often used as the recipient's address, and a private key for signing transactions, thus ensuring data security and maintaining user anonymity.

Digital signatures [76]: By combining hash functions and public key cryptography, digital signatures authenticate transactions, enabling recipients to verify the sender's identity.

Elliptic Curve Cryptography (ECC) [77]: Used mainly in blockchain, ECC generates smaller, more efficient digital signatures with its smaller key size and high security, making it the preferred technology for cryptocurrencies like Bitcoin and Ethereum.

Zero-knowledge proofs [78]: Using this technology, one party can confirm the accuracy of a claim to another party without disclosing the details of the claim.

Merkle Trees [79]: The Merkle Tree efficiently and securely validates large data volumes within the blockchain. Through hash functions, Merkle Trees connect blocks of data, forming a verifiable data structure.

Collectively, these cryptographic technologies establish the foundation for blockchain security and functionality, extending its application beyond cryptocurrencies to encompass a variety of decentralized applications.

#### 2.2.5. Decentralized Peer-to-Peer Networks in Agriculture and Animal Husbandry

Peer-to-peer (P2P) networks operate on a structure that is decentralized, where each computer in the network acts simultaneously as both client and server [80]. Unlike the conventional client-server model, P2P networks are decentralized, with every node contributing to data processing and transmission. This design significantly reduces the load of data transmission and storage, thereby enhancing system efficiency and reliability.

Decentralized peer-to-peer (P2P) networks enable direct data sharing among agricultural stakeholders. For example, in a crop trading scenario, a P2P network allows farmers to directly share real-time pricing and product availability with buyers, bypassing intermediaries. In livestock farming, P2P networks can facilitate collaborative data sharing between farmers and veterinarians, enabling faster responses to health issues and improving animal welfare. This decentralization enhances collaboration and efficiency in the agricultural ecosystem.

P2P networks are distinguished by several architectural types:

Pure peer-to-peer architecture: In this architecture, all nodes are equal, with no fixed network structure or central control point, and resource discovery relies on flood querying or random searches. Suitable for resource sharing and distributed searching, like the early Gnutella network.

Structured peer-to-peer architecture [81]: This architecture utilizes predefined topological structures (like Distributed Hash Tables (DHT)) to organize nodes and manage resources, providing an efficient and predictable method of resource location. Suitable for scenarios requiring precise searches and data consistency, such as certain distributed database systems.

Hybrid peer-to-peer architecture [82]: This architecture combines characteristics of pure P2P and client-server models, often with some central servers or special nodes assisting in resource discovery and network coordination. Suitable for scenarios that combine decentralized advantages with centralized management efficiency, like the BitTorrent network.

Each P2P architecture offers unique benefits but has limitations, making them suitable for different network environments and application needs. Understanding these architectures is crucial for making informed decisions in P2P network design and implementation. The schematic diagrams of the above three types of p2p networks are shown in Figure 5.

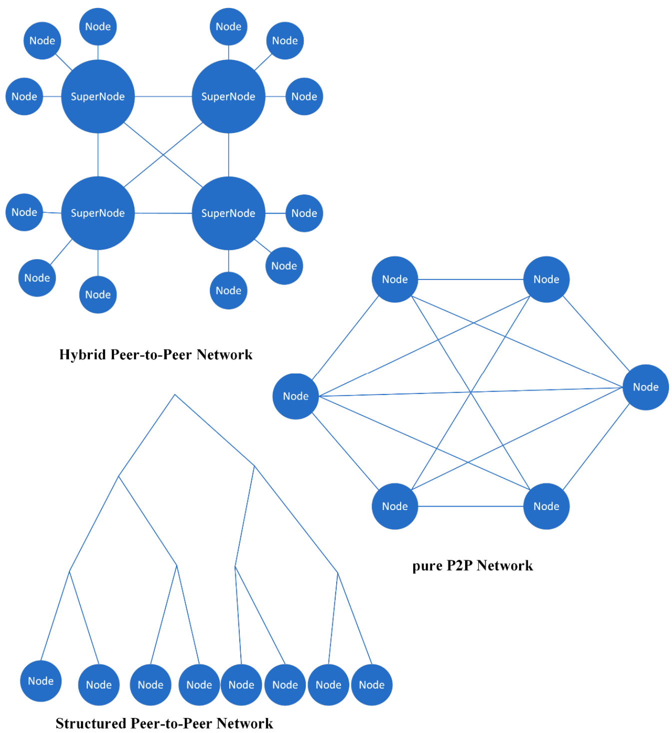


**Figure 5.** Three types of P2P networks.

## 3. Challenges and Motivations

Amid growing global concerns about food safety and the sustainability of farming practices, the agricultural and pastoral IoT are facing a range of pressing challenges. These challenges are primarily centered around data management, supply chain transparency, and product traceability, which require innovative approaches to enhance efficiency and reliability. This section centers on the challenges and motivations behind integrating blockchain technology into the agricultural and pastoral IoT

### *3.1. Current Challenges in Agricultural and Livestock IoT*

With the swift advancement of IoT technologies in agriculture and livestock management, significant changes have been initiated in these sectors. These technologies have revolutionized farms into highly automated and intelligent systems, thus enhancing production efficiency and the efficacy of resource management. Nonetheless, these advancements also introduce a range of challenges in data management.

Data Management:

The expansive deployment of IoT in agriculture and livestock management generates vast datasets concerning crop growth, climate changes, soil quality, and animal health. Managing these data effectively is crucial for refining production processes, elevating harvest quality, and ensuring food safety.

Firstly, the collection and storage of data present considerable challenges. Considering the volume and diversity of data, robust mechanisms are needed to maintain data integrity. Additionally, safeguarding data against corruption or tampering during transmission is vital for preserving its security and completeness.

Secondly, the challenge of data sharing and network efficiency is pivotal in the context of agricultural and livestock IoT. Information processing can be adversely affected by high data transmission volumes due to network congestion and delays. Therefore, managing these data efficiently and deciding which portions to upload and share is critical for optimal network performance.

Lastly, the challenges of data filtering and validity assessment are paramount. Identifying and extracting valuable data for insightful analysis and decision-making, given the constraints of limited resources, is essential. This necessitates sophisticated algorithms and analytical tools to distill the most relevant information from the extensive datasets for effective agricultural production and management.

In conclusion, the data management challenges in agricultural and livestock IoT encompass but are not limited to maintaining the integrity of data collection and storage, ensuring network efficiency, and conducting data filtering and validity assessment. Addressing these challenges demands an integrated approach using advanced technologies, innovative methods, and collaborative strategies to achieve optimal data management.

Security and Trustworthiness:

The integration of IoT technology brings forth security and trust issues. Securing data against unauthorized access or manipulation and fostering trust among stakeholders is critical. The supply chain involves extensive data exchange and processing from raw material acquisition through processing and distribution to the end product. The security of these phases is crucial for the supply chain's reliability and efficiency, with data security and tamper resistance as primary concerns. Unauthorized access or tampering can disrupt the supply chain and affect its credibility.

Cultivating trust among supply chain participants is also fundamental. Without trust, the exchange of critical information may be hindered, affecting efficiency. In an age of information surplus, finding valuable information and verifying its accuracy is essential for decision-making. Tackling these challenges requires a holistic approach, including technical safeguards, transparent communication, sophisticated data analysis techniques, and trust in the supply chain.

Privacy Protection:

With the widespread adoption of IoT systems in the agriculture and livestock sectors, safeguarding both commercial and personal information remains a pivotal concern. These systems collect extensive sensitive data—ranging from crop details and climatic patterns to soil conditions and livestock health—making robust data management essential for upholding farmers' privacy rights and protecting trade secrets. A key challenge lies in preventing unauthorized access and misuse of personal data, given that comprehensive datasets often include geographic locations, farming practices, and economic conditions. Additionally, the exposure of commercial information—such as production methodologies, yield figures, and marketing strategies—poses equally significant risks: breaches could result in severe financial losses and erode competitive advantages.

Beyond these immediate issues, the long-term implications for small-scale farmers warrant closer scrutiny. Many smallholders lack the technical infrastructure and financial resources to adopt blockchain-enabled IoT systems, heightening the risk of exclusion from modernized supply chains. Over time, this could widen the digital divide and exacerbate economic inequalities in the sector as technologically advanced enterprises capitalize on real-time data sharing, precision monitoring, and enhanced market access. Furthermore, blockchain's decentralized nature—while it promotes transparency—can inadvertently compromise privacy, making sensitive details (e.g., farmers' personal information, land-specific data, or business trade secrets) accessible to unauthorized third parties.

To mitigate these challenges and ensure responsible implementation of blockchain technology, it is vital to balance transparency with robust privacy protections. Selective disclosure and role-based access controls can shield high-value or personal data, while dedicated funding, training programs, and community-based resource centers can help smallholders overcome financial and technical barriers. Equally important are legal frameworks that safeguard personal and commercial information, along with continuous monitoring and assessment to evaluate the long-term socioeconomic impact on small-scale farmers. Through these collective efforts, blockchain-integrated IoT systems can drive efficiency and trust in agriculture and livestock management without marginalizing vulnerable stakeholders or compromising data security.

## *3.2. Technological Advancements in IoT and Blockchain for Agriculture*

### 3.2.1. Evolution of IoT in Agriculture

With IoT technology, both agriculture and livestock management have achieved greater efficiency, smarter operations, and sustainable practices. The following are key developments in IoT within these sectors:

Agriculture:

- Advancements in smart farming: IoT enables the integration of sensors across agricultural landscapes, facilitating real-time tracking of variables such as crop development, soil conditions, and weather changes, thus propelling the adoption of precision farming techniques.
- Efficient resource management: using IoT devices leads to significant reductions in wastage and a minimized environmental footprint by optimizing essential resources like water and fertilizers.
- Operational automation: automation of farm equipment, exemplified by automated irrigation systems and drones, enhances operational efficiency and diminishes the need for manual labor, thanks to IoT in agriculture.

- Supply chain management and product traceability: in agricultural supply chains, IoT technology has improved transparency and traceability substantially, thereby boosting food safety standards and reinforcing consumer confidence.

Livestock:

- Livestock health monitoring: livestock behavior and health are monitored using IoT technology, which helps in the timely detection and treatment of diseases and health issues.
- Feed management and animal welfare: IoT technology allows for more precise feed distribution and also enables monitoring of animal welfare, ensuring their growth in optimal environments.
- Ranch automation: IoT technology has made ranch management more automated, such as automatic feed distribution systems and health monitoring devices, reducing the need for human labor.
- Product quality tracking: in livestock management, IoT technology is also utilized to track the quality of meat and dairy products, from the ranch to the consumer, ensuring the high quality and safety of the products.

In summary, IoT technology's expansion in agriculture and livestock management profoundly enhances production efficiency, resource utilization, and product quality. These innovations not only refine conventional practices but also open avenues for more sustainable and eco-friendly methods of production. As technological progress continues, these sectors are expected to evolve further towards heightened automation and intelligence.

### 3.2.2. Emergence of Blockchain as a Solution

This subsection explores how blockchain is applied in the agricultural and animal husbandry IoT ecosystems:

Resolving Data Management Challenges:

- Immutable data records: Blockchain introduces a distributed ledger system where once records are created, they become unalterable. This aspect guarantees the integrity and trustworthiness of data gathered in the agricultural and animal husbandry IoT, including critical information on crop growth and climatic conditions.
- Enhancing data transparency and traceability: Blockchain enables comprehensive recording and tracking of agricultural products from production to consumption. This level of transparency not only improves supply chain visibility but also augments product traceability, optimizing the overall supply chain management.

Boosting Security and Trust:

- Decentralized framework: Blockchain's decentralization diminishes single-point failure risks, storing information across multiple network nodes. This enhances data security, significantly reducing risks of data loss or manipulation.
- Secured transactions: Utilizing blockchain for securely documenting transactions, such as trading and logistics of agricultural products, fortifies transactional security. The encryption of each transaction bolsters the security and transparency within the supply chain.

Enhancing Privacy Protection:

- Data encryption: blockchain's capability to encrypt data safeguards sensitive information like production costs, outputs, and trade secrets, preventing unauthorized access and breaches.
- Controlled access: it enforces the protection of sensitive and confidential data by allowing only authorized individuals to access specific datasets.

Blockchain technology, distinguished by its immutability, decentralization, transparency, and secure encryption, presents potent solutions for data management, security enhancement, trust establishment, and privacy protection within the IoT frameworks of agriculture and animal husbandry. Therefore, a new era of efficiency, reliability, and security in agriculture and animal husbandry is heralded by integrating blockchain with IoT in these sectors.

## 4. Applications of Blockchain in Agricultural and Animal Husbandry IoT

This article delves into the significant role of blockchain technology within IoT applications in agriculture and animal husbandry and its importance for data processing and control, supply chain management, efficient resource allocation, building trust frameworks, and ensuring system security and privacy. First, we introduce how blockchain can improve data processing and control, enhance data transparency, immutability, and traceability, and provide a reliable data management platform for agriculture and animal husbandry. Next, the article examines how blockchain technology can improve supply chain management, focusing on its capability to improve both transparency and efficiency via a decentralized record-keeping mechanism.

Subsequently, we discuss how blockchain can promote efficient resource allocation, automate the execution of agricultural contracts and transactions through smart contracts, optimize resource distribution, and reduce operating costs. In addition, this article also explains how blockchain can help build a trust framework by providing an immutable record and verification mechanism to enhance trust among participants.

Finally, we focus on discussing the strategies and technologies of blockchain in ensuring system security and privacy, exploring how to use blockchain encryption and access control functions to protect agriculture and animal husbandry IoT data from unauthorized access and the risk of leakage. IoT in agriculture and animal husbandry can be enhanced through this series of analyses and how it can drive the industry towards a more efficient, transparent, and secure direction.

### *4.1. Data Management*

In traditional agricultural and pastoral IoT systems, data storage and management face issues such as susceptibility to attacks, data isolation, and inefficiency. Blockchain technology offers an effective solution: it enhances data security and transparency through distributed ledgers, while the application of smart contracts improves the efficiency of business processes. This not only solves existing problems but also promotes the modernization and digital transformation of agriculture and pastoralism.

#### 4.1.1. Data Management and Storage

This subsection explores the significance of data management and storage in modern technology applications, particularly in the fields of agricultural IoT and livestock IoT. We analyze the challenges present in current systems, as well as challenges related to data sharing, security, and privacy, which significantly impact data management. Additionally, the enhancement of data management and storage within agricultural and livestock IoT through blockchain solutions is discussed.

Article [73] discusses the extensive deployment of IoT devices in modern smart agriculture and aquaculture, enabling remote monitoring capabilities. These devices facilitate optimal management of resources and maximization of profits by precisely monitoring environmental parameters like temperature, dissolved oxygen levels, and pH values. However, the process involves challenges in data sharing and security management, particularly concerning privacy protection and data processing transparency. The reliance on central servers for current IoT security solutions not only incurs high energy and resource costs but also poses risks of single-point failures, undermining analysts' trust in data management.

To tackle these issues, papers [83–86] introduce blockchain technology as an innovative solution, revolutionizing agricultural sharing by removing single-point failure vulnerabilities and enhancing data immutability and transparency. Its application extends beyond establishing smart farms and tracking food supply chains to bolster agricultural data security and trustworthiness. Despite facing challenges such as high computational demands for consensus algorithms, integration with existing systems, and large-scale agricultural data storage, blockchain offers an effective, distributed, privacy-focused framework for data management and sharing, potentially driving innovation and growth in the agricultural sector.

Acknowledging blockchain technology's role in managing agricultural data and exploring its consequences for interconnected sectors becomes imperative. In China, the livestock industry plays a crucial role in agricultural output and farmers' income but is susceptible to risks like disease outbreaks, natural disasters, and market volatility. To alleviate these risks, livestock insurance has been implemented, but inefficiencies and high costs persist due to the absence of real-time, reliable data on livestock environments. Market opacity and fluctuations further complicate accurate market forecasting for breeders. Addressing these challenges, article [6] proposes a blockchain and IoT-based environmental monitoring platform for livestock sheds. By assigning unique digital identities and RFID ear tags to each animal, the platform ensures precise matching of livestock with their digital profiles, enabling real-time monitoring by government and financial institutions. This system, powered by blockchain and IoT technologies, not only guarantees data authenticity and regulatory transparency but also automates livestock insurance processes through smart contracts. This significantly enhances efficiency and transparency while reducing costs, potentially fostering widespread adoption of livestock insurance.

Moreover, the fusion of blockchain technology with the IoT has been crucial across multiple sectors, especially in improving product traceability and ensuring the safety of food. A wide array of organizations and institutions now harness blockchain technology to document transactional data. These applications of technology have proven to be highly effective in securing the traceability of agricultural goods and food safety. For example, by storing information related to agricultural commodities and food production on a decentralized blockchain network, stakeholders can perpetually track every stage of distribution, thereby guaranteeing the integrity and transparency of each transaction and phase of production. Although blockchain technology has found widespread use in the financial sector, supply chains for agriculture, and food traceability, its adoption for managing breeding data remains notably less frequent.

Confronted with the escalating volume of breeding data and the increased demand for concurrent database access, traditional data storage approaches are facing significant performance hurdles. Blockchain provides a decentralized alternative to these conventional methods. Addressing these challenges, article [87] introduces an effective and secure framework for storing crop breeding data at high throughput utilizing enhanced blockchain technology. Distinct from conventional blockchain structures, this framework organizes breeding information by geographical location and breeding stages, allocating it across various databases while encapsulating the core data's summary within a streamlined blockchain. This framework not only facilitates swift and secure data storage and retrieval but also seamlessly scales alongside growing datasets, thereby elevating the system's operational efficiency. Furthermore, the framework's robust security and high efficiency eliminate the need for high-caliber computing resources in both its database and blockchain layers, substantially lowering the financial burden associated with system hardware.

#### 4.1.2. Data Sharing and Security

In this subsection, we thoroughly investigate the fundamental importance of data sharing and security within IoT applications, with a particular emphasis on their role in agricultural and livestock IoT. By integrating blockchain into IoT frameworks, we anticipate a substantial enhancement in aspects of data sharing and security, which are crucial for bolstering the dependability and operational efficiency of IoT implementations in the agricultural and livestock domains. The use of blockchain is expected to revolutionize these sectors, offering a more secure and efficient means of handling and processing critical data.

Paper [88] highlights the escalating issues of information silos and data exchange within the IoT domain, emphasizing the need for improved privacy and security. Current centralized data management and authentication approaches show clear limitations in addressing these challenges. Consequently, paper [89] introduces a novel solution integrating blockchain with edge computing within an authentication system. This solution utilizes an optimized Practical Byzantine Fault Tolerance (PBFT) algorithm, enhancing data storage security and traceability for end-user activities. It incorporates dynamic name resolution strategies and Elliptic Curve Cryptography (ECC) to establish a distributed authentication mechanism, improving communication security and data synchronization efficiency. Additionally, the paper introduces algorithms for dynamic cache space optimization through smart contracts, improving hit rates and reducing latency. Simulation results indicate improvements in latency and hit rates, advancing IoT framework efficiency, data stewardship practices, and security verification.

Currently, the application of blockchain technology in data storage encounters several challenges. The inherent chain-like structure of blockchain, characterized by its time irreversibility and immutability, leads to continuous data accumulation. This accumulation necessitates extensive resources for data entry and storage, thus hindering the blockchain system's operational efficiency. Furthermore, within the blockchain, data are presented solely in a chain structure. Internal transactions are bundled and stored collectively without revealing any interrelationships among them.

Paper [90] introduces a collaborative management model designed to alleviate the storage burden on blockchain systems by storing all traceable data on cloud servers, as depicted in Figure 6. When new data are added, the system identifies and incorporates this hash into the new block. This process facilitates the swift identification of the parent transaction hash, enabling the timely assembly of the full traceability chain. Such a mechanism significantly reduces the storage demands on the blockchain infrastructure.

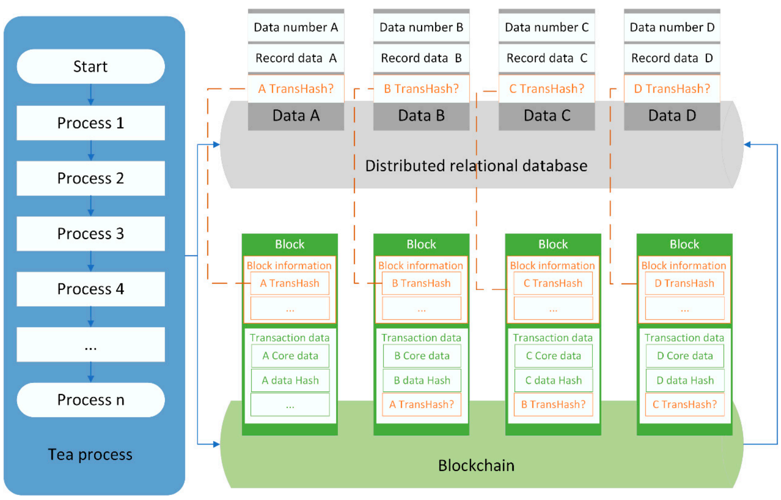


**Figure 6.** Data storage design for the tea traceability system in [90].

While two-layer or multi-layer frameworks in blockchain systems primarily address the engagement of regulatory bodies and the privacy of sensitive information across nodes, focusing on business-level data storage, they do not alter the blockchain's internal storage architecture. The framework proposed by paper [90] diverges from these conventional multi-layer designs.

As illustrated in Figure 6, this study employs the tea supply chain as a case study, where the processes numbered 1, 2, 3, and beyond sequentially represent tea harvesting, processing, and packaging, among other activities. Users sequentially record each step of the tea process in the database. A local server logs data from tea process 1 in the initial stage. These data are then entered into the blockchain system unconsolidated. Subsequently, through the application of machine learning techniques, anomalous data points within the traceability data are filtered out. These cleansed data are then committed to the blockchain as a transaction, including elements such as TransHash, the record number, the transaction hash, and key data from the preceding step, signaling the imminent consolidation of data. Following each submission, the system assesses the completion of the prior process. If the transaction is deemed complete, a TransHash operation related to the preceding step is executed at the point of data submission; otherwise, further submissions are barred. The final step entails the linking of data, at which point the data from process 1 becomes immutable and non-erasable. By embedding transaction data from process 1 into the transaction initiated in process 2, it becomes feasible to swiftly identify preceding transaction data during searches without the necessity of scanning all network nodes. Additionally, in the event of data deletion, restoration is achievable via a data rollback process. This framework significantly bolsters the reliability and efficiency of information sharing within the tea supply chain, thereby furnishing robust technological support for the tea industry's sustainable growth.

As the IoT network expands, issues such as security and integrity arise due to the increase in data, along with the complexity brought by different parameters and data formats tracked by IoT devices, affecting data quality. Problems such as data loss, inconsistency, accuracy issues, and ambiguity in large volumes of data are prevalent. Despite IoT's crucial role in enhancing agricultural efficiency, ensuring the secure processing and reliability of data remains a primary concern.

To mitigate these issues, paper [91] introduced an innovative strategy, namely the integration of Ethereum-based blockchain technology with IoT sensor data. Utilizing a private blockchain network coupled with a PoW consensus algorithm, this technique guarantees the integrity and protection of irrigation data. Blockchain, as a distributed ledger technology, confers benefits, including data transparency, permanence, and decentralization, thus significantly enhancing the security and dependability of data handling, particularly in the context of irrigation data management within precision agriculture. This fusion of IoT and blockchain not only addresses prevailing issues but also charts a novel course for the advancement of smart agriculture.

The environmental parameters of high-value crops in smart farms are usually very sensitive, and the transmission and processing of these data in existing systems are often only protected by simple passwords, making them susceptible to hacking and tampering by cyber attackers. Data security is an urgent issue, especially when central control processing units use remote login monitoring.

To tackle this problem, paper [92] proposes a solution based on blockchain to enhance security for IoT data transfer. This system transmits data through a wireless sensor network to an integrated microcontroller at the farm for fusion processing, then encapsulates the data using blockchain algorithms and finally stores them in a cloud database. This method leverages blockchain's decentralized and tamper-proof characteristics to secure and establish trust in data, offering an innovative and secure solution for IoT data management.

Similarly, in smart agriculture, IoT technology primarily facilitates the accurate collection and processing of crop and environmental data, aiming to elevate agricultural productivity and quality. Nonetheless, the evolution of these technologies has brought forth various security and privacy concerns. Devices in the IoT, including sensors, encounter various security challenges due to their limited processing capabilities and battery duration. These challenges encompass risks of data tampering and the fraudulent representation of devices.

Addressing these challenges, paper [93] introduces an innovative framework that combines the IoT with blockchain to enhance data security and reliability within smart farming. This framework employs a blockchain layer that interfaces with sensor devices to authenticate identities, execute operations, and log information in a cloud database. This structure ensures the security of records and resistance to tampering while also protecting the confidentiality of crucial data such as crop verification. This approach significantly enhances the integrity and tamper-resistance of data, addressing the security vulnerabilities inherent in IoT devices and boosting resilience.

Table 1 provides a summary of different research areas and their applications as explored in the literature pertaining to data management.

**Table 1.** Data management related papers.

| Targeted Challenges | Papers | Short Introductions | Blockchain-Enabled Opportunities |
|---|---|---|---|
| Data Management and Storage | [73] | Storing data on the blockchain reduces energy and processing resources costs. | Storing data on the blockchain reduces storage costs and increases transparency. |
| | [6] | Data related to animals enables immediate monitoring and automates insurance procedures through secure recording and management on the blockchain. | |
| | [87] | This article presents a novel blockchain framework optimized for storing high-throughput crop breeding data, structured by geographical location and breeding stages, to enhance security and efficiency. | |
| | [83–86] | Emphasized the difficulties faced in managing and storing data within IoT frameworks. | Proposed blockchain as an innovative solution to address these challenges, leveraging its decentralized nature to enhance data management capabilities and reduce reliance on central servers. |
| Data Sharing and Security | [88] | This paper explores the complexities surrounding data sharing and the management of security within IoT ecosystems. | Blockchain brings revolutionary changes to data management and sharing in IoT. |
| | [89] | Utilizing an optimized PBFT consensus algorithm achieves enhanced data storage security and traceability of terminal activities. | A distributed authentication mechanism was designed, enhancing communication security and data synchronization efficiency. |
| | [90] | A cooperative storage management system was developed to enhance the efficiency of storing and querying data on the blockchain, incorporating mechanisms for data tracking, rollback, and protection against tampering. | Enhanced the trustworthiness and information-sharing efficiency of the tea supply chain. |

**Table 1.** *Cont.*

| Targeted Challenges | Papers | Short Introductions | Blockchain-Enabled Opportunities |
|---|---|---|---|
| Data Sharing and Security | [91] | The paper combines IoT technology with Ethereum-based blockchain to enhance precision agriculture by securing and making irrigation data more reliable. | By integrating blockchain technology with IoT for agriculture, decentralized data management is introduced, which enhances security, transparency, and integrity in smart irrigation systems. |
| | [92,93] | This study explores the enhancement of data security in smart farming through the application of blockchain technology, focusing on protecting sensitive crop growth parameters. | Blockchain technology presents a groundbreaking potential for managing IoT data, offering a secure, decentralized, and immutable system for handling sensitive data in agriculture. |

The table consolidates key findings from various studies that address two major themes: data management and storage (references [6,73,83–87]) and data sharing and security (references [88–93]). Overall, it demonstrates how blockchain-based solutions have been proposed to tackle the challenges of data handling in IoT and agriculture-related contexts. Below is a concise analysis of the advantages, disadvantages, and the best results emerging from these studies.

Advantages: Enhanced trust and transparency: Many studies (e.g., [6,73]) emphasize that storing data on the blockchain can reduce costs associated with energy or manual oversight while simultaneously increasing transparency in data records. This is particularly beneficial in sensitive domains such as agriculture and livestock management, where traceability and accountability are paramount.

Improved security: References [88,90,92] underscore that blockchain's cryptographic mechanisms mitigate tampering and unauthorized access. Moreover, integrating blockchain with IoT (references [91,93]) offers a robust way to protect sensitive data (e.g., growth parameters or irrigation information), thus strengthening the overall security framework.

Decentralized data management: Several papers ([83–86]) identify blockchain's decentralization as a powerful tool for distributing storage and management tasks across nodes, diminishing dependence on a single central server. This can lead to higher fault tolerance and resilience against single points of failure.

Potential for streamlined operations: By automating processes such as insurance claims (reference [6]) and implementing frameworks for high-throughput crop breeding data (reference [87]), blockchain solutions can reduce manual overhead, shorten processing times, and foster more efficient data handling workflows.

Disadvantages: high computational and energy costs: Although some studies ([73]) claim reduced costs in certain areas, blockchain frameworks—especially those using energy-intensive consensus mechanisms—may still demand considerable computational power. This challenge may negate some of the purported efficiency gains, particularly in resource-constrained IoT settings.

Scalability issues: References that discuss high-throughput use cases (e.g., [87]) often point out that while blockchain can secure and track data effectively, scaling these systems to accommodate large volumes of data remains a challenge. Current blockchain infrastructures may not always cope well with the speed and frequency of data generation in real-world IoT applications.

Complexity of integration: Merging blockchain with existing IoT infrastructures (references [83–86]) demands careful planning and technical expertise. Network architecture, communication protocols, and consensus mechanisms must be aligned to ensure compatibility and optimal performance.

Best Results: Hybrid (On-/Off-Chain) storage approaches: Some papers suggest combining on-chain and off-chain solutions to balance security with scalability. For instance, large or sensitive datasets can be stored off-chain, while key integrity hashes remain on-chain to maintain authenticity and traceability.

Efficient consensus mechanisms: References [89,91] note that using optimized consensus algorithms (e.g., PBFT) can simultaneously improve the speed of data processing and maintain strong security guarantees.

Cross-domain integration: Beyond agriculture, studies highlight that blockchain's decentralized approach could enhance trust in any ecosystem requiring reliable, tamper-proof data management. By adopting a multi-layered architecture (e.g., local data aggregation plus decentralized verification), solutions can adapt to diverse use cases in manufacturing, supply chain, or smart cities.

Emphasis on collaboration and standardization: A key takeaway is the importance of establishing common standards and protocols, ensuring that disparate IoT devices and data sources can interoperate seamlessly within a blockchain framework. This collaboration among researchers, practitioners, and industry players can accelerate widespread adoption and foster more robust, secure systems.

In summary, the table's entries illustrate that blockchain-based solutions can offer significant benefits for data management, storage, sharing, and security—particularly in IoT- and agriculture-related contexts—while also facing challenges related to scalability, integration complexity, and energy costs. The most promising advancements stem from using hybrid storage models, efficient consensus protocols, and clear collaborative frameworks to optimize both performance and trust in decentralized environments.

### *4.2. Supply Chain Management*

In the contemporary sphere of agriculture and livestock production, the transparency and traceability of supply chains are of paramount importance. These aspects are vital for assuring product quality, fostering consumer trust, and adhering to regulatory standards. The capability to trace agricultural products' journey from farm to table is not just a requirement of informed consumers but also essential for conforming to global standards and market expectations.

Traditional centralized supply chain management systems, while meeting regulatory and coordination demands to a certain extent, face inherent challenges in modern agriculture and livestock contexts. Centralized systems are prone to single points of failure, where disruptions in one link of the supply chain can affect the entire system's operation. Moreover, the lack of transparency and mechanisms for information sharing results in low trust among supply chain participants, potentially leading to data falsification and resource waste.

In contrast, blockchain technology offers a novel solution through its decentralized architecture. Its immutability ensures data authenticity, its transparency enhances trust among stakeholders, and its smart contracts significantly improve operational efficiency. These features make blockchain technology particularly effective in improving the operations of traditional supply chains, especially in scenarios where information exchange and collaboration are critical, such as in the agriculture and livestock industries.

This section delves into how technological innovations, especially the synergy of blockchain and the IoT, are ushering in transformative changes in transparency and traceability within the agricultural and livestock supply chains. The application of these technologies enables companies to offer an extensively transparent view of the product lifecycle, encompassing every phase from production and processing to distribution and final sale. This methodology is instrumental not only in combating food fraud and contamination but also in significantly enhancing the overall efficiency and sustainability of supply chain operations.

#### 4.2.1. Transparency and Information Sharing in Supply Chains

In this subsection, the focus is on discussing the importance of supply chain transparency and its impact on various stakeholders (such as producers, suppliers, distributors, and consumers). This paper examines the use of technological solutions, such as blockchain and IoT, to facilitate immediate data sharing and visualization across the entire supply chain. This includes tracking the sourcing of raw materials, production workflows, inventory control, and logistics monitoring.

In paper [7], the authors introduce a cutting-edge blockchain-based traceability framework aimed at tackling food safety challenges within the agricultural sector in India. The foundation of this framework is a private blockchain network encompassing key stakeholders such as farm producers, suppliers, distributors, wholesalers, and consumers. By encrypting and distributing important information across the blockchain, this network guarantees the security of confidential data. Additionally, the paper thoroughly explores how smart contracts are utilized within the agricultural supply chain. These contracts are instrumental in overseeing and orchestrating all transactions and communications throughout the supply chain.

Additionally, the research delves into the architectural and design aspects of the system, focusing on evaluating key elements, including hardware configuration and bandwidth. The conducted trials demonstrated the system's superior efficiency under controlled conditions, with significant performance metrics. By detailing these technical specifications, the blockchain-enabled traceability framework aims to reduce risks associated with food adulteration. The system's potential benefits include enhanced traceability, efficiency, and public health safety, prompting further investigation and innovation in business models that integrate blockchain technology and the IoT.

Similarly, paper [94] addresses issues of information loss, incomplete data, and difficulty in tracking within the Indonesian sugar industry supply chain, proposing a blockchain technology-based intelligent decision support system. The reliance on centralized databases by conventional information systems results in data tampering and a substantial trust deficit. Additionally, the complexity of the supply chain network and geographical distribution results in difficulties in effectively tracking and monitoring supply chain activities.

The solution presented in this paper capitalizes on the decentralization, immutability, and transparency inherent to blockchain technology. This novel system significantly enhances supply chain transparency and efficiency by establishing a secure, transparent, and immutable environment for data sharing. Additionally, it integrates smart contracts and IoT technology, thereby augmenting the supply chain's performance and bolstering trust among consumers and stakeholders. This innovative application of blockchain technology is expected to significantly enhance information management across the supply chain, thereby boosting operational efficiency and the overall effectiveness of the sugar industry's supply chain management. This approach presents a significant stride towards resolving the prevalent challenges and optimizing the supply chain processes within the sugar industry in Indonesia.

Furthermore, in paper [95], the authors explore the intricacies of the agricultural supply chain, focusing specifically on the hurdles encountered by small-scale farmers. Central issues identified within traditional supply chain management encompass a lack of transparency, limited credibility, and a skewed distribution system disadvantageous to small-scale farmers. These challenges stem primarily from the centralized structure of supply chain management and the opacity regarding essential information. This situation obstructs small-scale farmers' efforts to achieve fair trading conditions in a competitive market environment. The study introduces an innovative solution that employs blockchain technology alongside a cyber–physical system (CPS) to authenticate agricultural produce's quantity and quality. This approach aims to increase the reliability of the supply chain. CPS's distinguishing aspect in agricultural management lies in its combination of hardware and software solutions, ensuring comprehensive coverage and dependability throughout various stages.

Figure 7 encapsulates the CPS-based information management architecture within the agricultural supply chain. The subsequent sections provide an in-depth examination of each component and the dynamics of information flow. Information traverses from farms, warehouses, factories, and stores to sensor servers and back. In this context, the term "sensor server" refers to a central database that stores data collected by monitoring devices positioned in agricultural fields.

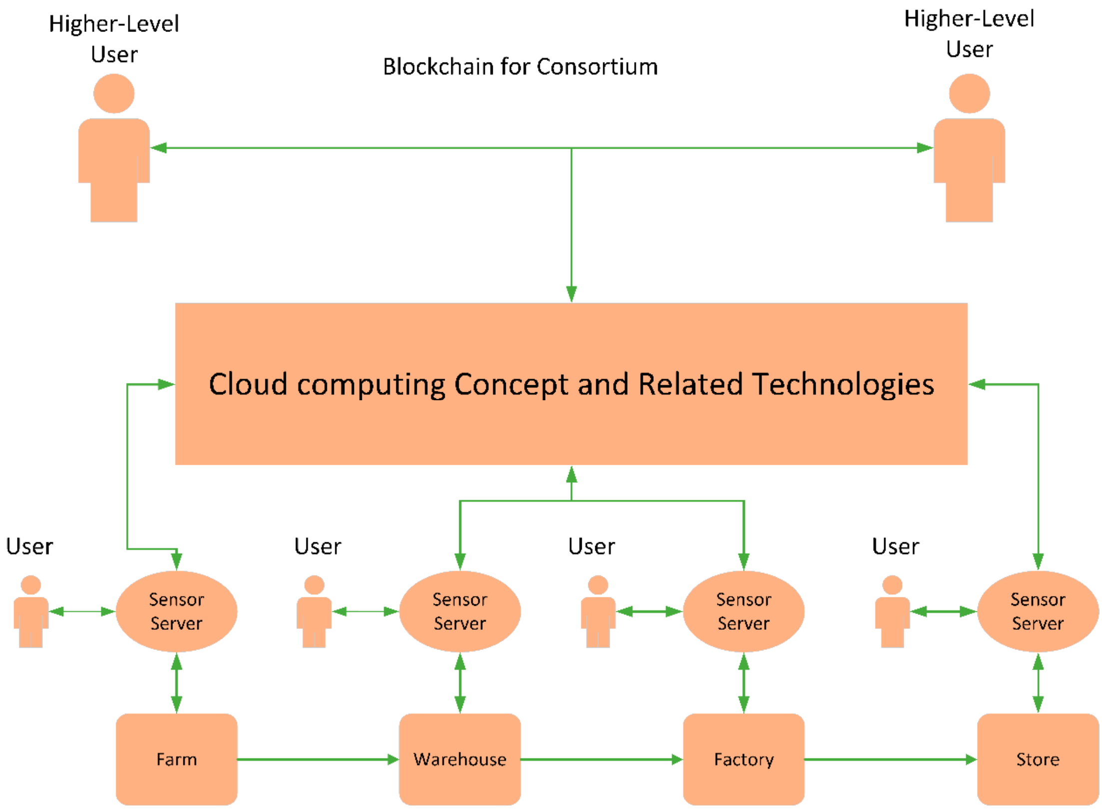


**Figure 7.** Information management based on cyber–physical systems in agricultural supply chain systems [95].

In a CPS setting, it is notable that sensors and monitoring devices are generally small, with restricted data transmission capacities and a limited operational scope. Furthermore, fields are often equipped with numerous monitoring devices to ensure adequate coverage, rendering individual manual interaction with each device impractical. This necessitates the adoption of an intermediary layer, such as a server, to aggregate data from all devices, enabling immediate user access to this information. In Figure 7, the physical components—farms, warehouses, factories, and stores—represent the tangible environment (field), where bidirectional information flow is facilitated by monitoring devices capable of both gathering essential data and receiving operational commands from the sensor server.

The user refers to individuals overseeing the physical environment, enabling them to retrieve data from the sensor server. "Higher-Level User" encompasses entities seeking an overarching view of the agricultural supply chain, including managers, shareholders, customers, and governmental bodies. Nonetheless, due to concerns over privacy and competitive dynamics, there may be a reluctance to share comprehensive field data with higher-level users. Moreover, these higher-level users, often located in remote regions, might not have the capability for direct, dedicated network connectivity to the field. This is where cloud computing and related technologies become pivotal, serving as an intermediary that collates and abstracts essential information from disparate locations to offer a global perspective to higher-level users. Ultimately, this blockchain-centric solution represents a significant stride towards establishing a more equitable and accessible market for small-scale agricultural stakeholders.

#### 4.2.2. Traceability and Quality Assurance of Supply Chains

This section delves into the crucial role of product traceability within supply chains, emphasizing its significance in assuring product quality and safeguarding consumer safety. It outlines the strategies for implementing traceability systems in supply chains and the associated challenges, such as utilizing identification technologies like RFID and QR codes, as well as approaches for data collection, processing, and analysis. This section further explores how traceability is applied to tackle food safety challenges and handle quality management issues.

In paper [96], the authors introduce a model that integrates IoT and blockchain technology, particularly tailored for the governance of supply chains in agriculture and food sectors. The core of this model is an innovative energy-efficient routing protocol aimed at reducing energy consumption and extending system life. Particularly, in contrast to the conventional Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol, this protocol improves network stability by 23% and extends the time to the death of the first node to 463 rounds, compared to 168 rounds for the LEACH protocol. Moreover, the energy usage of this protocol is 68% less than that of LEACH, resulting in a 112% extension of the network's lifespan. The blockchain element acts within the supply chain to securely and privately share data, effectively eliminating vulnerabilities associated with centralized information networks and enhancing the system's security and accessibility.

Additionally, the model meticulously incorporates IoT technology to gather agricultural data accurately. In this context, IoT applications include monitoring crop growth, soil temperature, pest infestations, and soil quality, providing essential insights for farmers about crop yields, disease prevention, and soil management. These insights aid in enhancing agricultural practices and crop management. Furthermore, IoT technology tracks and documents crop growth data, while the blockchain component updates the food safety status in real time within the supply chain. This reduces the vulnerability of information networks, enhancing security, availability, and ease of access.

Moreover, paper [97] addresses traceability and quality assurance challenges, focusing on the agricultural product supply chain through the use of consortium blockchain and smart contracts. This innovation tackles the prevalent issues of information asymmetry, data tampering, and loss, which traditional traceability systems, dependent on technologies like RFID and QR codes, struggle with due to their limitations in data security and integrity.

The essence of this solution lies in its utilization of blockchain's distributed, immutable, and decentralized properties. By deploying consortium blockchain and smart contracts, the system ensures secure and transparent record-keeping across the supply chain and facilitates efficient management and regulation of participant interactions. This approach not only enhances the traceability and quality assurance of agricultural products but also minimizes the dependency on vulnerable centralized systems, thereby reducing trust costs and improving overall supply chain integrity. By storing every transaction record on the blockchain's immutable ledger, the system guarantees heightened transparency and traceability throughout the supply chain. This enhancement significantly boosts overall efficiency and effectively tackles critical issues like food safety.

Additionally, in livestock farming, cold-chain transportation is an indispensable link, and blockchain technology significantly enhances traditional cold-chain transportation. In paper [98], the researcher emphasizes the significant increase in demand for fresh farm produce via online shopping platforms amid the COVID-19 pandemic. In this context, the difficulty of maintaining the quality of agricultural products increases. Although traditional cold chain distribution effectively keeps products fresh, its problem of information asymmetry leads to an inability to effectively regulate preservation activities, increasing the possibility of supply chain members abandoning preservation efforts. Furthermore, the increased risk of cold chain disruptions poses challenges to e-commerce platforms. Due to the inconsistency in the completion of all processes in traditional cold chain supply chains, suppliers often lack the motivation to continue preservation efforts after receiving wholesale funds, thus failing to ensure product freshness and directly affecting consumer demand for fresh agricultural products.

The paper proposes an innovative blockchain-based solution to these challenges. Blockchain, as a secure and transparent distributed database, eradicates the information asymmetry inherent in cold chain preservation. It enables supply chain stakeholders to obtain real-time data on product freshness and delivery, thereby enhancing control over product preservation. Blockchain's traceability and tamper-proof features effectively monitor preservation history and temperature fluctuations within the cold chain in real time, enhancing preservation outcomes. The blockchain's traceable and immutable features efficiently monitor the history of preservation and real-time temperature changes in the cold chain, enhancing preservation results. However, the paper also acknowledges the limitations of blockchain application in specific contexts, highlighting the necessity for future investigations into the nuanced effectiveness of blockchain technology across various scenarios.

Additionally, paper [99] concentrates on the challenge of determining the origin of farm products within agricultural supply chain systems, especially in agriculturally prominent nations such as Bangladesh. Existing agricultural supply chain systems, reliant on manual paper records, struggle to track detailed information about agricultural products, such as their origin, location, and quality. Additionally, due to the centralized architecture of supply chains, reliable traceability services for agricultural products are unattainable. The present system faces major challenges, such as insufficient transparency, ineffective tracking capabilities, and the absence of certification for those within the supply chain. These problems result in consumer skepticism about the authenticity of the products and pose potential health hazards to the public.

The study introduces a revolutionary approach, merging self-sovereign identity (SSI) and blockchain technology to create a reliable traceability system for agricultural products. Integrating a Decentralized Key Management System (DKMS) with SSI significantly improves authentication, direct transactions, privacy, data integrity, and traceability across the supply chain. Furthermore, the research presents an innovative packaging and labeling method using the Fantom blockchain network, optimizing origin verification processes and enhancing efficiency, cost-effectiveness, scalability, and security. This method greatly increases supply chain transparency and accountability.

Table 2 provides a summary of different research areas and their applications as explored in the literature pertaining to supply chain management.

**Table 2.** Supply chain management related papers.

| Targeted Challenges | Papers | Short Introductions | Blockchain-Enabled Opportunities |
|---|---|---|---|
| Transparency and Information Sharing in Supply Chain | [7] | This article introduces a blockchain framework aimed at enhancing traceability and safety within India's agricultural industry by consolidating stakeholders and utilizing smart contracts for managing the supply chain. | This article outlines a blockchain framework designed to enhance traceability and safety in India's agricultural sector by integrating stakeholders and employing smart contracts for supply chain oversight. |
| | [94] | The proposed system in the paper incorporates blockchain to tackle the complexity and trust issues within centralized information systems in the supply chain. | Blockchain technology in this design offers enhanced traceability, real-time data information, and reduced manipulation, leading to more reliable and transparent supply chain management. |
| | [95] | The study presents a new blockchain technology design for the agricultural supply chain, focusing on traceability, scalability, and fair share amount assignment, enhanced by a cyber–physical system, public service platform, and an improved ant colony optimization algorithm. | In this model, blockchain technology ensures transparent transactions and immutable records, establishing a consortium among producers and addressing critical issues to optimize trust and profitability. |
| Traceability and Quality Assurance in Supply Chain | [96] | This article presents an advanced IoT and blockchain model for agriculture, tackling issues such as data security and energy efficiency. It proposes an innovative energy-efficient protocol for IoT-based agriculture, which surpasses the LEACH protocol in terms of network stability and energy usage. | In this framework, blockchain technology enhances data security, diminishes the risk of manipulation, and boosts the resilience of IoT-based agricultural systems, promoting sustainable and efficient food production practices. |
| | [97] | The paper proposes a method utilizing consortium blockchain and smart contracts to manage agricultural products across the supply chain, enhancing transparency, reliability, and security by eliminating centralized authorities. | This solution employs blockchain to establish a secure, transparent, and immutable ledger for transactions, enhancing integrity and efficiency within the agricultural product supply chain. |
| | [98] | This paper investigates how blockchain technology can verify the freshness and sustainability of fresh agricultural produce within the supply chain. It focuses on the relationship between efforts to preserve freshness, marketing initiatives, and how blockchain is applied in both traditional and enhanced systems. | Blockchain's integration aids in the continuous effort to maintain freshness by enhancing transparency and accountability in the supply chain. This reduces the need for promotional and goodwill expenses, thus preserving profit margins without compromising investments in environmental sustainability. |
| | [99] | The paper introduces a blockchain architecture that operates on a P2P network designed to enable dependable tracking within supply chains. Without explicitly mentioning self-sovereign identity and decentralized key management, this architecture utilizes the Fantom blockchain network to ensure efficient transactions. | Incorporating blockchain technology enhances the tracing and verification of agricultural products by improving their authenticity, integrity, and confidentiality. This integration enables faster and more reliable transactions throughout the supply chain. |

The table above compiles research on blockchain implementations aimed at enhancing transparency and information sharing in the supply chain (references [7,94,95]) and traceability and quality assurance in the supply chain (references [96–99]). These studies collectively highlight how blockchain can help address issues of trust, data management, and operational efficiency in various agricultural and supply chain contexts. Below is an overview of the key advantages, disadvantages, and best results drawn from these papers.

Advantages:

Improved traceability and transparency: Several studies ([7,94,95,97]) focus on how blockchain's immutability and distributed ledger features enable end-to-end traceability and real-time information sharing. This transparency is crucial for verifying product authenticity, monitoring quality, and enhancing consumer trust.

Heightened security and reduced manipulation: By employing decentralized frameworks (e.g., [95,96,99]), blockchain mitigates risks inherent in centralized systems, such as data tampering or single points of failure. Smart contracts also automate transactions and reduce the likelihood of human error or intentional fraud.

Enhanced operational efficiency: Studies like [96] propose energy-efficient protocols for IoT-based agriculture that can work synergistically with blockchain, thus supporting more sustainable and cost-effective operations. Additionally, automating key processes (e.g., product verification and payment transactions) cuts down on administrative overhead.

Fair distribution and incentive mechanisms: Reference [95] integrates blockchain with methods like improved ant colony optimization to ensure fair allocation of resources and transparent record-keeping. Such mechanisms help align stakeholder incentives, reduce conflicts, and improve overall system governance.

Disadvantages:

Complex implementation and integration: While blockchain holds promise, merging it into existing supply chain systems demands substantial technical expertise and infrastructure ([94,95]). Compatibility issues with legacy databases or platforms can slow adoption and add integration costs.

Scalability and performance bottlenecks: As supply chains grow, so do data throughput and transaction volume. Many blockchain networks are still grappling with scalability ([96,99]). High latency and limited throughput can hinder real-time operations and large-scale deployments.

Energy and resource constraints: Although some protocols aim to be energy-efficient ([96]), blockchain consensus mechanisms—especially proof-of-work—can be resource-intensive. In settings where cost margins are tight (e.g., agriculture), these extra overheads can be prohibitive.

Regulatory and standardization hurdles: The decentralized nature of blockchain often clashes with existing regulatory frameworks. Cross-border supply chains, in particular, must navigate diverse regulations, posing challenges for uniform adoption and standardization ([7,97]).

Best Results:

Integrated IoT–blockchain solutions, combining blockchain's security and transparency with IoT's real-time data capture (e.g., [96]), yield powerful monitoring systems for agriculture and supply chains. This synergy ensures high-quality data collection, secure storage, and rapid decision-making.

Consortium and permissioned blockchains, references [97,98] explore models where multiple stakeholders, such as producers, distributors, and regulatory bodies, form a consortium blockchain. This approach balances the benefits of decentralization with controlled access to the network, supporting both traceability and data privacy.

Advanced consensus mechanisms and optimization algorithms: studies like [95] and [96] demonstrate that optimizing or replacing traditional consensus protocols (e.g., using improved ant colony algorithms, specialized proof-of-stake, or PBFT variants) can reduce resource consumption, increase transaction throughput, and maintain strong security guarantees.

Focus on sustainability and value preservation: References [96,98] highlight how blockchain can improve not only data integrity but also sustainability—by validating freshness of produce, minimizing waste, and controlling energy usage. These benefits strengthen market confidence and can lead to better profit margins and environmental outcomes.

In summary, the research in this table suggests that blockchain can significantly enhance transparency, traceability, and efficiency within agricultural and broader supply chain operations. While challenges related to scalability, integration complexity, and regulatory compliance remain, the most promising advancements come from combining blockchain with IoT, employing energy-efficient consensus mechanisms, and forming multi-stakeholder consortium blockchains. These approaches offer a robust foundation for more secure, transparent, and sustainable supply chain ecosystems.

### *4.3. Efficient Resource Allocation*

In the agricultural and pastoral IoT field, operators can manage key resources such as water, feed, and fertilizers more efficiently by leveraging blockchain and smart contracts. The application of this technology not only optimizes resource allocation and ensures precise supply but also improves overall production efficiency.

In paper [100], the amalgamation of blockchain and IoT technology was employed to tackle principal concerns within the tea production supply chain. The challenges faced by traditional tea production and supply chains include high risks and inefficiencies dependent on manual control, as well as a lack of traceability throughout the process, leading to insufficient resource management and low efficiency. Although IoT technology has made progress in data collection and automatic control, challenges still exist in ensuring the effective allocation and use of resources. These limitations impact the tea production and supply chain's performance in terms of resource conservation, environmental monitoring, and overall production efficiency.

To address these issues, the paper proposes a tea resource management platform that synergizes the transparency and unchangeability of blockchain technology with the automation and resource management capabilities inherent in IoT. This platform features an IoT layer equipped with specific chips in devices that autonomously capture environmental data via wireless transmission and RFID technology. These data are processed using an adaptive weighted fusion method, enhancing accuracy. Concurrently, the blockchain layer of the platform utilizes smart contracts to record and track these data, thereby increasing transparency and security. This integration effectively facilitates decentralized oversight and ensures data consistency. Moreover, the platform implements energy-efficient automated controls, including automatic adjustments based on environmental data and optimal irrigation strategies, thus minimizing water resource wastage.

Moreover, papers [101–104] all mention that in the field of agricultural water resource management, the main issue currently faced is how to effectively and accurately manage and monitor water usage. Paper [105] mentions that although the development of IoT technology has enabled the incorporation of energy-efficient connected devices into water distribution networks, which can automatically monitor water consumption, existing agricultural IoT systems tend to choose hardware devices with low power consumption and limited resources. This choice highlights a core issue: the limited capability of IoT devices to directly interface with blockchain infrastructure necessitates the introduction of a third-party intermediary, like an IoT gateway, to facilitate communication between sensor devices and blockchain endpoints. This not only escalates infrastructure costs but may also compromise the credibility of data collected from the field.

To tackle the identified problem, paper [106] presents an innovative solution within a decentralized water resource management system: enabling low-power IoT devices to directly engage with the public blockchain network. Such devices are capable of transmitting data to smart contracts independently, without the necessity for intermediary infrastructure components like IoT gateways. This approach not only diminishes infrastructure costs but also significantly boosts data trustworthiness by bypassing third-party intermediaries. The practicability of this solution was corroborated through experimental evidence, demonstrating that devices with limited resources can efficiently engage with the public blockchain with only a minimal increase in energy consumption. This advancement provides a more effective and reliable technological avenue for the management of agricultural water resources and furnishes pertinent insights for the advancement of analogous domains. The water management system is shown in Figure 8.

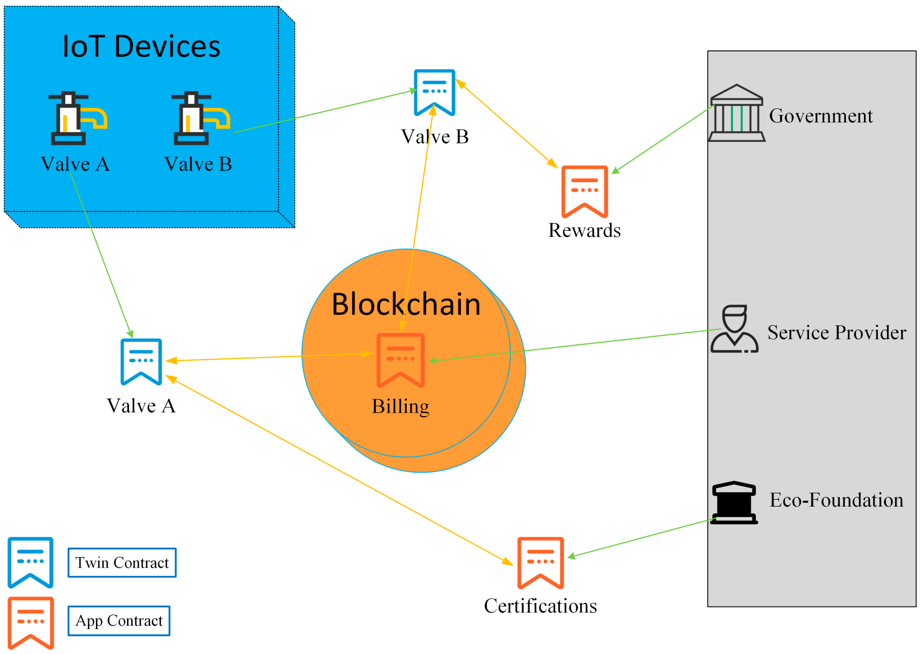


**Figure 8.** Water management system in [106].

The water resource management framework comprises smart contracts for decentralized applications that execute the water management protocols. It envisages two categories of smart contracts for facilitating interactions within the platform: Twins and Apps. Twins serve as simplified digital counterparts of IoT devices, conceptualized as "smart twins" (illustrated through Valves in Figure 8). In addition to logging data from the devices, they provide a universal interface for the smart contracts of applications tasked with implementing the specific business logic required by the application (for instance, Billing, as shown in Figure 8). Each Twin contract retains only the device's owner and time-stamped data readings (pertaining to water metrics). Twin, serving as an interface, introduces two key functions: getValue() for retrieving data and setValue() for updating data, where setValue() can only be called by the corresponding device and getValue() can be invoked by any entity initiating a transaction. Consequently, Apps smart contracts can utilize this functionality to issue bills for water consumption, distribute rewards, or confer certifications.

In a similar vein, paper [107] delves into a critical challenge within the agricultural sector: the effective management of water resources. Contrasting with paper [106], which focused on allowing resource-limited IoT devices to directly connect with blockchain networks to reduce infrastructure expenses and enhance data dependability, paper [107] investigates the enhancement of agricultural water resource management's efficiency and security through the amalgamation of IoT and blockchain technologies. As agricultural technology progresses, especially with the application of IoT, water resource management is evolving towards greater automation and intelligence. However, this advancement also presents new challenges, particularly in ensuring efficient water resource allocation and utilization, as well as in monitoring and maintaining seed quality. Traditional IoT systems may fall short in these areas, often lacking comprehensive monitoring and control over resource allocation and use.

To tackle these challenges, paper [107] introduces an innovative approach that integrates IoT and blockchain technologies. The essence of this approach lies in leveraging blockchain technology to optimize resource management, with a particular focus on water resources. In this system, blockchain is employed not merely for bolstering data security and transparency; it crucially underpins resource distribution and monitoring. Blockchain technology ensures more equitable and effective water resource distribution and enhances the capability to monitor water usage. Additionally, this integration significantly improves the accuracy and efficiency of monitoring seed quality. The system facilitates real-time observation and automated control of water resource utilization and seed status in the agricultural production process through the implementation of smart electronic devices at the hardware level, markedly elevating the overall efficiency and output of agricultural production.

Beyond agricultural IoT, blockchain technology also holds substantial development prospects within the pastoral IoT sector. Within the framework of enhancing smart livestock farming, deploying IoT technology in this area faces multiple challenges, mainly related to data security and safeguarding. These challenges are rooted in the inherent security vulnerabilities of IoT devices, the risk of cybercrime, and complexities in everyday livestock management, including greenhouse gas emission control and repetitive task processing. Additionally, the lack of transparency in existing IoT systems within supply chain management complicates the process of tracing product origins and ensuring quality.

To address these challenges, paper [108] introduces an innovative system, IoT-BC-SLF (Internet of Things–blockchain–smart livestock farming). This system leverages blockchain technology to forge a decentralized, enduring, and tamper-resistant ledger that documents every transaction and piece of data within the livestock supply chain. This approach markedly enhances the data's transparency and security, allowing for precise tracking across each phase of the supply chain, hence improving product traceability. Furthermore, by augmenting the security of IoT devices, the system effectively thwarts hacking attempts and data leaks, safeguarding the completeness and dependability of livestock data. The IoT-BC-SLF system not only elevates the production efficiency of livestock farming but also advances animal health management and environmental conditions through automated and intelligent measures. This offers farmers more efficient and accurate livestock management strategies. As a result, the system serves a critical function in enhancing the overall sustainability of livestock farming and lays a solid groundwork for the future development of intelligent agriculture.

Table 3 provides a summary of different research areas and their applications as explored in the literature pertaining to resource allocation.

**Table 3.** Resource Allocation Related Papers.

| Targeted Challenges | Papers | Short Introductions | Blockchain-Enabled Opportunities |
|---|---|---|---|
| Resource Allocations | [100] | The paper introduces a novel architecture that combines blockchain and IoT technologies to improve resource traceability and management within the tea production supply chain. | Blockchain technology offers transparency, decentralized supervision, and tamper-proof records, enhancing resource management efficiency in tea supply chains. |
| | [101–104] | In the field of agricultural water resource management, the main challenge currently faced is how to effectively and accurately manage and monitor water usage. | Not using blockchain technology. |

**Table 3.** *Cont.*

| Targeted Challenges | Papers | Short Introductions | Blockchain-Enabled Opportunities |
|---|---|---|---|
| Resource Allocations | [105,106] | The paper describes a system rooted in blockchain technology designed to support low-power, resource-limited IoT devices in directly engaging with a public blockchain to support sustainable water management practices in agriculture. | Merging blockchain with IoT devices in this framework creates avenues for transparent, economical, and secure water management strategies in agriculture. |
| | [107] | The approach integrates IoT and blockchain technologies to optimize resource management in agriculture, focusing on water resources and seed quality monitoring, enhancing security, transparency, and agricultural output. | Blockchain technology offers opportunities for equitable resource distribution and precise monitoring in agriculture and addresses security and transparency challenges in smart livestock farming and supply chain management. |
| | [108] | This system utilizes IoT and blockchain technologies to boost resource management efficiency in smart livestock farming through enhanced data transparency and security. | Blockchain technology improves resource management in livestock IoT, including the management of animal feed, fertilizers, and greenhouse gas emissions control. |

This table summarizes research on resource allocation in agriculture, focusing on how IoT and blockchain can combine to enhance efficiency, transparency, and security. Below is a concise overview of key advantages, disadvantages, and notable outcomes from these studies ([100–108]).

Advantages:

- Enhanced traceability and accountability: blockchain-led records mitigate fraud and oversight issues, as demonstrated in tea production ([85]) and livestock resource management ([108]).
- Secure and transparent resource management: integrating blockchain with IoT devices ([105–107]) enables accurate water-use tracking and seed quality monitoring, offering tamper-proof data and reducing reliance on centralized authorities.
- Potential for cost savings and sustainability: decentralized systems can cut intermediaries, streamline processes (e.g., water management), and promote more responsible resource usage.

Disadvantages:

- Integration and technical complexity: incorporating blockchain into traditional IoT infrastructures requires specialized protocols for low-power devices and advanced expertise, posing adoption challenges ([105,106]).
- Scalability and performance constraints: large transaction volumes and limited network capacity can hinder broader deployment.
- Energy and infrastructure demands: some consensus mechanisms or additional hardware may raise operational costs, possibly limiting feasibility for smaller-scale or resource-constrained settings.

Best Results:

- IoT–blockchain synergy for resource optimization: Real-time data monitoring combined with decentralized validation supports more equitable and efficient distribution of water and feed resources ([105–108]).
- Tailored protocols for low-power solutions: Developing specialized blockchain architectures for constrained devices ([105,106]) curbs overhead without sacrificing security.

- Holistic agriculture management: Integrating sensor data and smart contracts helps streamline activities such as irrigation scheduling and livestock feeding, boosting productivity and environmental stewardship.

In summary, these works demonstrate blockchain's promise to improve agricultural resource management by increasing transparency, security, and sustainability. However, practical challenges such as technical complexity, scalability, and energy use must be addressed to fully realize these benefits in diverse farming contexts.

*4.4. Building Trust Frameworks*

In today's digital era, the establishment of a robust and effective trust framework is critically important, particularly in scenarios involving intricate transactions and interactions with multiple stakeholders.

Initially, blockchain technology ensures the authenticity and durability of data via its intrinsic feature of immutability. Each transaction documented on the blockchain undergoes verification by several nodes within the network, securing its permanent record that is impervious to alteration or erasure. This immutability lays a solid groundwork for establishing a reliable trust framework, allowing all involved parties to depend on the veracity and permanence of these records.

Additionally, the inherent transparency of blockchain significantly bolsters trust. In numerous blockchain applications, the details of transactions and records are accessible to all engaged parties. Although participant identities may be shielded through anonymity or pseudonymity, this level of transparency ensures that all stakeholders have real-time visibility of transaction records, thereby enhancing the system's transparency and fostering a heightened sense of accountability.

In summary, the significance of devising a trust framework is paramount, especially in contexts involving complex transactions and engagements with multiple parties. Blockchain, as a pioneering technology, is instrumental in fostering such a trust framework through its unalterable data recording and transparent transactional procedures.

In the realm of the IoT, particularly in relation to the supply chains for agricultural products, significant issues of transparency and traceability are prevalent. Consumers frequently encounter challenges in authenticating the claims made on product labels regarding sustainable agricultural practices and social responsibility. This dilemma not only undermines consumer confidence but could also lead to potential risks in food safety. Furthermore, the presence of counterfeit and misleading environmental marketing claims poses a substantial challenge to the trust established between consumers and brands, consequently influencing consumer purchasing decisions.

To address this issue, paper [109] introduced a Third-Party Certification (TPC) approach that amalgamates smart contracts and blockchain tokens, aimed specifically at certifying plant-based agricultural products. Originating at the harvesting phase, this approach allows for the precise tracking and authentication of each harvest's origin and volume. By utilizing Non-Fungible Tokens (NFTs) and improved Ethereum smart contracts, the method in the paper not only increases the system's transparency but also strengthens its tamper-resistance, effectively enhancing consumer trust in the product's origin and quality.

In a similar context, paper [110] introduced blockchain and encryption technologies; this approach leverages decentralized, unalterable, and traceable features, enhancing agricultural product traceability. It not only ensures a robust and transparent method for managing traceability data, but it also applies encryption algorithms to ensure data security on the blockchain, safeguarding data integrity with fine-grained access control.

The agricultural product traceability system (APTS), depicted in Figure 9, encompasses the entire lifecycle of agricultural goods, including production, processing, storage, distribution, and retail. This process encompasses a broad range of participants, including farmers, processors, warehouse managers, logistics service providers, retailers, and end consumers, all subject to the strict oversight of regulatory bodies. These authorities are responsible for overseeing identity verification, access management, and data governance. As illustrated in Figure 9, the system's logical framework captures comprehensive data spanning the agricultural product's journey from inception to consumption, incorporating a range of data types, including structured and unstructured. To maintain data integrity and confidentiality, structured data are encrypted before logging, and unstructured data are stored externally after being digitally signed. The system is distinguished by several technological advancements: (1) It is immutable, guaranteeing the data's authenticity, accuracy, and permanence. (2) It utilizes decentralized storage to mitigate the risks associated with centralized systems. (3) In addition to protecting the privacy of data publishers, it provides adaptable access mechanisms to tackle the issue of data ownership and control within a blockchain framework. (4) It employs traceable smart contracts that, in the event of a quality or safety issue with an agricultural product, automatically collate and upload pertinent data from involved parties to the system, thus preventing data tampering, deletion, or forgery and enabling the accurate determination of the incident's origin. This framework's emphasis on data encryption and flexible access control is pivotal for the system's security and trustworthiness, setting it apart from other blockchain-based traceability systems in agriculture. These innovations successfully balance data privacy concerns and the necessity for efficient data sharing, thereby enhancing the dependability and integrity of the system.

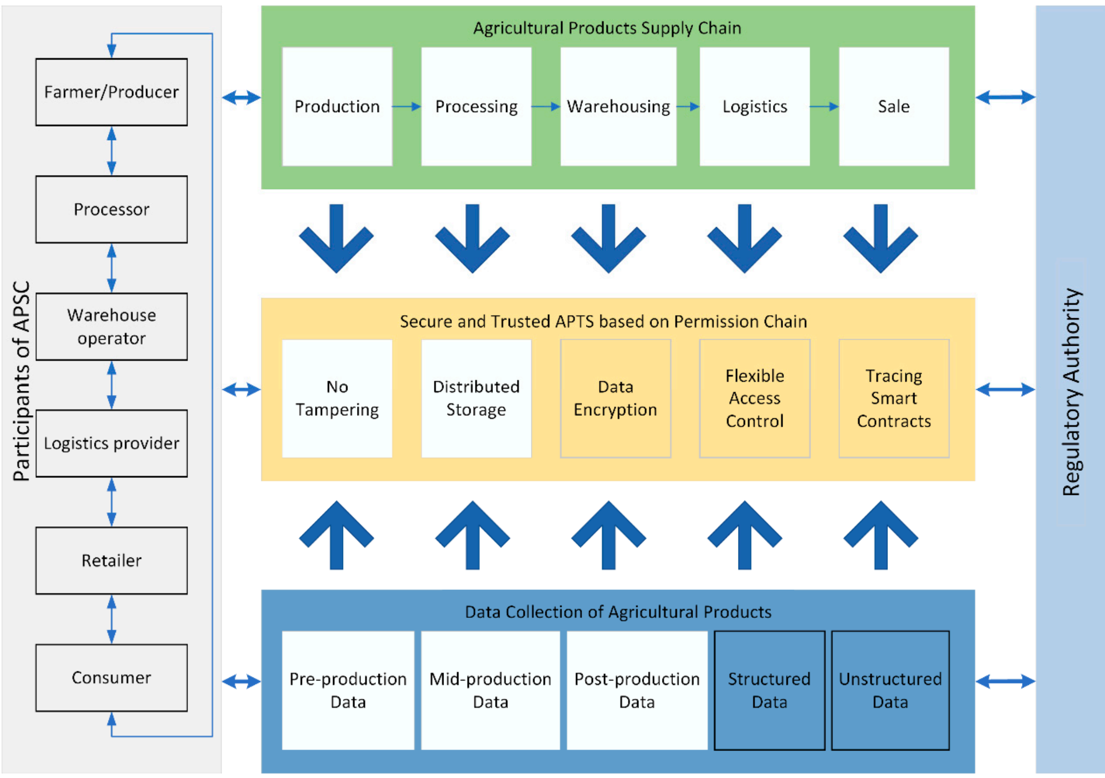


**Figure 9.** The system logic architecture of agricultural product traceability system in [110].

In addressing trust issues, paper [111] focuses on blockchain technology within the IoT for overcoming challenges in transparency and information sharing, particularly within the organic agriculture sector. The current reliance on distributed database systems and centralized processing methods can lead to information loss or tampering, thus triggering a crisis of trust among consumers. Targeting the core issues of information asymmetry and opacity, the paper proposes a new framework combining blockchain and edge computing technologies. Blockchain's immutable, transparent, and decentralized nature establishes a more reliable ecosystem for the organic agriculture supply chain, further improved by edge computing's role in enhancing data processing's cost-efficiency and effectiveness. By clearly defining key roles and recording and verifying all related activities on the blockchain, this specially designed framework effectively manages information flow, enhancing the supply chain's transparency and trustworthiness.

Contrasting with the focus of paper [111], paper [112] delves into novel methodologies for addressing trust issues within the IoT, especially in the agricultural sector, by employing blockchain technology. The backdrop of this study is the rapidly declining consumer trust in the food industry, primarily driven by frequent food safety incidents such as mad cow disease, with specific apprehensions about the origins and safety of food products. This scenario has amplified the demand for more robust food traceability systems. Current tracking systems, ranging from traditional paper-based records to digital QR code-based solutions, are plagued by inefficiencies and a lack of thorough information verification, posing significant challenges for small and micro enterprises due to their prohibitive costs and complexity of implementation.

In [113], it is suggested that blockchain can enhance consumer trust in agricultural and pastoral product supply chains, while paper [114] delves into the complexities and solutions related to IoT implementation in smart agriculture. As IoT technology becomes increasingly prevalent in agricultural settings, notably in areas like real-time monitoring, environmental sensing, and communication, it facilitates the shift from traditional farming practices to smart agriculture. This progress, however, introduces new challenges, especially concerning security and privacy protections. These challenges are accentuated when IoT is integrated with cutting-edge technologies like cloud computing, fog computing, and machine learning, impacting not just the technological dimensions but also the trust relationship between consumers and producers. A trust framework based on blockchain, utilizing the Ethereum network and smart contracts, is introduced to tackle these challenges. This approach enhances security, reliability, traceability, and transparency in IoT-enabled smart agricultural systems, effectively bridging the trust gap between producers and consumers and providing new insights into the security and development of smart agriculture.

Meanwhile, paper [115] explores addressing trust-related challenges within the agricultural IoT landscape through blockchain technology. It sets the scene by highlighting the evolution of smart agricultural systems, particularly the adoption of wireless technologies for monitoring crop conditions and gathering data, where data security and the reliability of communications are paramount. These systems frequently encounter obstacles such as network congestion and data security vulnerabilities, with conventional approaches falling short in ensuring trustworthy data exchange and preventing unauthorized access. To overcome these hurdles, the article proposes an innovative amalgamation of blockchain and machine learning. This methodology automates the collection and transmission of data through intelligent devices and employs multivariable linear regression techniques to assess environmental factors, thereby affirming the reliability of the data transmission system. Concurrently, integrating a reliable system within the blockchain framework significantly strengthens communication security, diminishes communication disruptions, and safeguards the integrity and confidentiality of data in transit. This pioneering strategy not only elevates the security and reliability of data and communication within smart agricultural systems but also presents a viable resolution to trust and security issues plaguing agricultural IoT environments.

In the realm of the IoT, numerous devices and systems are vulnerable to compromise, resulting in diminished trust. To counteract this, a significant trend in traditional IoT research, as illustrated in papers [116–118], has been the integration of IoT with blockchain technology to mitigate trust issues. Focusing on the agricultural and pastoral sectors, paper [119] presents an innovative approach, harnessing both blockchain and IoT technologies, to address trust challenges associated with IoT data sharing in agriculture. This research is motivated by the growing impact of climate change on agriculture, which heightens risks linked to weather, soil conditions, and pest infestations. These escalating risks exert economic strains on farmers and pose threats to regional food security. Traditional risk management strategies, such as agricultural insurance, face limited adoption in developing countries, mainly because of mistrust in sharing and accessing risk data through established centralized agricultural information systems. In this context, although IoT devices have great potential in real-time monitoring and data sharing, they also encounter risks that impact the data's reliability and trustworthiness. Employing these devices within centralized data management systems faces challenges like single points of failure and authentication issues. As a solution, the study adopts blockchain technology, utilizing self-sovereign identity (SSI) and Verifiable Credentials (VCs) to improve the security and reliability of sharing data. This approach effectively boosts the trustworthiness of IoT devices in agricultural data sharing, reducing reliance on centralized institutions and addressing trust issues. Additionally, the study introduces a decentralized oracle mechanism for safely accessing risk-related data in smart contracts, further accelerating the agricultural insurance claim process and effectively implementing risk management strategies. Overall, this method not only improves the credibility and security of data sharing but also reduces reliance on centralized institutions, effectively solving the trust issue in IoT data sharing in agriculture.

Table 4 provides a summary of different research areas and their applications as explored in the literature pertaining to building trust frameworks.

**Table 4.** Building Trust Frameworks Related Papers.

| Targeted Challenges | Papers | Short Introductions | Blockchain-Enabled Opportunities |
|---|---|---|---|
| Building Trust Frameworks | [109–113] | In the agricultural and livestock product supply chain, consumers do not trust messages that are not guaranteed. | The trust consumers have in agricultural products is enhanced by blockchain by ensuring the integrity and authenticity of information. |
| | [114,115,119] | Proposed is a framework leveraging blockchain and IoT technologies to address consumer trust issues in managing risks in agricultural production. | By utilizing blockchain technology, significant improvements in trust and security have been achieved in agricultural IoT data sharing. |
| | [116–118] | Addressed the trust concerns arising from potential harm to IoT devices and systems and examined how merging IoT technology with blockchain technology can resolve this issue. | These studies demonstrate the potential of blockchain technology when integrated with IoT to restore trust through a secure and transparent framework for managing device and system operations. |

This table presents studies addressing how blockchain and IoT-based frameworks can enhance trust in agricultural and livestock supply chains. Below is a concise overview of their advantages, disadvantages, and best outcomes:

Advantages:

Integrating blockchain and IoT in agriculture has brought significant advancements in trust, transparency, and security within agri-food supply chains. Studies [110–113] highlight how this integration ensures data integrity, thereby enhancing consumer confidence in product quality and origin. Moreover, distributed ledgers reduce reliance on third-party intermediaries, as noted in [114,115], protecting against data tampering and leakage while enabling secure and reliable data sharing. Additionally, frameworks proposed in [114,115,119] combine blockchain's immutability with IoT's real-time monitoring capabilities, paving the way for new management models that enhance risk management and traceability. Furthermore, research [117,118] demonstrates that integrating IoT with blockchain creates a trackable, closed-loop system capable of quickly detecting and responding to security threats, ensuring higher levels of trust and security in agricultural operations.

Disadvantages:

Despite its potential, integrating blockchain and IoT in agriculture faces several challenges that hinder large-scale adoption. High implementation costs and technical barriers, as highlighted in [111–113], remain significant obstacles, particularly for small-scale farmers who may struggle with hardware, software, and operational expenses. Data quality and standardization also pose challenges, as blockchain's immutability relies on accurate and reliable input; errors or the lack of standardized sensor data, as noted in [115,116], can undermine system credibility. Privacy and regulatory concerns further complicate adoption, with many agricultural organizations and individuals reluctant to share detailed data, creating a tension between transparency and privacy, as discussed in [117,118]. Additionally, scalability and performance bottlenecks limit blockchain's ability to handle high-frequency IoT data, straining throughput, speed, and storage capacity, which poses significant challenges for large-scale deployment.

Best results:

Combining blockchain and IoT presents a promising solution for creating secure and transparent trust frameworks, particularly in supply chains, by ensuring reliable data, automated risk management, and end-to-end visibility. This integration not only restores consumer confidence but also enhances the efficiency of risk mitigation, as studies demonstrate significant improvements in monitoring devices and systems, enabling the swift detection and resolution of potential threats or malfunctions. While these frameworks are currently applied in agriculture and livestock, their broader applicability extends to other sectors where data integrity and consumer trust are critical, showcasing their versatility and potential for wider adoption.

### *4.5. Ensuring System Security and Privacy*

Integrating blockchain technology into agricultural and pastoral IoT systems significantly boosts their defense against data manipulation and cyber threats. Blockchain's decentralized structure enhances system resilience by removing any single point of failure. Once information is logged, the blockchain's encryption linking each block makes modifications nearly impossible, rendering any tampering attempts easily detectable. Furthermore, the use of cutting-edge encryption safeguards data during transmission and storage. Blockchain's transparency and traceability permit all stakeholders to review transaction logs and data history, facilitating the swift identification and segregation of dubious activities. The implementation of smart contracts reduces human intervention, thereby decreasing the potential for fraud and errors. Moreover, by enabling IoT devices within a blockchain framework to share data storage duties, the system's redundancy and resistance to attacks improve. Together, these characteristics guarantee the security and dependability of agricultural and pastoral IoT frameworks against cyber risks.

In paper [120], the authors present a new method focusing on data security and privacy issues arising from IoT usage in agriculture. While IoT enhances monitoring and management, it also introduces risks like data tampering and counterfeit device connections. These security vulnerabilities not only threaten the safety of agricultural production but can also lead to incorrect decisions and resource waste. For example, inaccurate data may result in over-irrigation or insufficient fertilization, affecting crop yield and quality.

To tackle these concerns, the paper recommends using blockchain technology for IoT security management. The distributed and immutable data recording characteristics of blockchain provide robust security for IoT data. Blockchain technology records all data collected by IoT devices in a transparent, immutable database, ensuring data authenticity and completeness. Furthermore, blockchain's decentralized structure reduces the likelihood of system-wide attacks, while its identity verification and access control features ensure that data access is restricted to authorized individuals. This innovative approach, which combines blockchain and IoT, not only enhances data security but also optimizes the agricultural production decision-making process.

As one of the most widely applied technologies, the essence of the IoT is to connect smart devices through wired or wireless networks, enabling them to facilitate various real-time applications. However, these devices often have a heterogeneous nature with limited memory and processing capabilities, making traditional security protocols unsuitable for IoT devices. Therefore, ensuring the security of IoT systems has become a crucial issue. Papers [121–123] mention that blockchain is being used as the latest solution in various fields.

Thus, in agricultural irrigation systems, as mentioned in paper [124], the extensive deployment of IoT technology has made remote monitoring and control of these systems a reality. These systems depend on numerous sensors and devices for crucial irrigation analysis and data gathering. However, as the number of IoT devices grows, so does the complexity and significance of ensuring data security and privacy. IoT systems encounter several security challenges, including data tampering and unauthorized access. Traditional IoT systems usually adopt centralized data storage and management, which are susceptible to network attacks, including single-point failures and data breaches. In such systems, ensuring data integrity and secure communication between devices is challenging, with each node potentially being a target for attack. Moreover, managing device authentication and data access control becomes challenging in IoT environments with many devices and users.

To tackle these challenges, the paper proposes a new solution: improving IoT security management using blockchain technology. Blockchain technology's distributed ledger offers a decentralized, secure, and transparent approach to managing data within IoT systems. It secures all data gathered and transmitted by IoT devices, making it resistant to tampering. This security is achieved through data encryption and its storage on a distributed ledger, with each block of data interconnected with the preceding one. Additionally, blockchain provides robust mechanisms for authentication and access control, ensuring that only verified users and devices have the ability to access and control the system, facilitated by smart contracts. The decentralized framework of blockchain also enhances the reliability of IoT systems by reducing reliance on any single server or storage location, thereby diminishing the risk of single-point failures. This approach effectively overcomes the security management challenges faced by IoT, making it particularly beneficial for sectors like agricultural irrigation.

In the field of unmanned aerial vehicles (UAVs) in the agricultural and pastoral IoT, paper [125] proposes an innovative framework named SP2F, which utilizes blockchain and deep learning technologies. This approach aims to overcome the vulnerabilities inherent in traditional centralized security systems, such as single-point failures and scalability issues. The SP2F framework enhances security and privacy through a dual-layer privacy engine that integrates blockchain with smart contracts and an enhanced Proof of Work (ePoW) mechanism, effectively mitigating the risk of data contamination. Additionally, it employs a Sparse Autoencoder (SAE) to transform sensitive data into a secure encoding format, offering protection against inference attacks. To enhance the framework's effectiveness, a Stacked Long Short-Term Memory (SLSTM)-based system is employed for training and evaluating the performance of the dual-layer privacy engine. This comprehensive solution not only addresses the existing limitations of conventional security measures but also introduces a new strategy for safeguarding IoT applications within the realm of agriculture.

The field of IoT faces major attacks, including various threats during the data sensing and collection process. For instance, in jamming attacks, attackers interfere with the original signal's data by sending noise signals, which may lead to IoT devices obtaining incorrect sensing data. Side-channel attacks entail acquiring sensitive data from IoT devices via indirect means like power usage, electromagnetic emissions, timing, and heat properties. Malicious code injection involves embedding harmful code into physical devices, leading to irregular device behavior. Furthermore, malicious node injection attacks consist of incorporating bogus nodes into the network to interfere with the data exchange among legitimate nodes or to capture their data. These attack methods indicate that protecting IoT devices from compromise is an important and complex challenge. To address these issues, some papers [126,127] recommend the adoption of blockchain as a method to improve IoT device security, highlighting its distributed ledger and peer-to-peer network features, offers a resource-intensive but effective method to strengthen security, although integrating it directly with IoT devices presents challenges. Therefore, specific architectures need to be designed to achieve this goal, balancing resource limitations. In these studies, the concept of blockchain-enhanced IoT security and its experimental results have been implemented and verified.

In the IoT field, Distributed Denial of Service (DDoS) attacks are a significant and persistent threat. DDoS attacks are a common cyber-attack method where a multitude of manipulated devices simultaneously send requests to a designated target, overwhelming the target's service or network capacity and preventing it from providing normal services. Given the large number of devices and their lower security levels, these devices in the IoT environment become prime targets for attackers. For example, attackers can exploit security vulnerabilities in IoT devices to turn them into a "botnet" for launching DDoS attacks. The characteristics of the IoT environment, including the large number of devices, diversity, and strong connectivity, make IoT devices prone to being tools for DDoS attacks. Numerous IoT devices are deficient in robust security protocols, including encryption and authentication measures, because they were not adequately considered in the design phase. Existing solutions to DDoS attacks often focus on traditional network environments rather than being specifically designed for IoT. These solutions may not be suitable for the unique environment of IoT, such as performance challenges encountered when managing a vast array of devices and data volumes. Papers [128,129] suggest that blockchain is a decentralized, tamper-proof, and transparent data management mechanism, which has potential value in enhancing security in IoT environments. For instance, blockchain can be used to strengthen device authentication and data integrity verification and provide distributed security defense mechanisms. Future research can focus on how to integrate blockchain technology more effectively into IoT environments to improve defenses against DDoS attacks. Additionally, research can explore how to use machine learning and AI technologies to predict and identify DDoS attack patterns and how to implement lightweight security measures in IoT devices.

IoT technology has significantly improved agricultural production efficiency and resource utilization with smart agriculture, yet it also introduces challenges related to security and privacy. Existing security solutions, mainly based on cloud computing and IoT, have certain limitations, particularly concerning data storage and the security of communications. IoT devices themselves also present security risks and can be used for cyber-attacks and data breaches, issues that urgently need to be addressed.

Paper [130] introduced an intelligent agricultural safety monitoring framework that combines cloud technology with blockchain technology, enhancing the system's reliability and security. While the application of IoT in agriculture has enhanced efficiency and resource utilization, it has concurrently presented challenges regarding security and privacy. Traditional security methods rely on cloud computing and the IoT, with limitations in data protection and communication security. Data leakage and network attacks are risks associated with IoT devices, which urgently need to be addressed. To strengthen the monitoring and security of intelligent agriculture, the paper proposes combining blockchain, cloud servers, and smart farms.

Figure 10 illustrates the multi-layered structure of the smart agriculture application framework. Initially, the smart farm layer encompasses a variety of sensor apparatuses with distinct functionalities within the agricultural domain. This layer is constituted by IoT sensor equipment deployed across each parcel of land, incessantly generating data related to device condition and operational metrics. Such data are conveyed to cloud services via edge gateways or intermediary devices linked to these sensors.

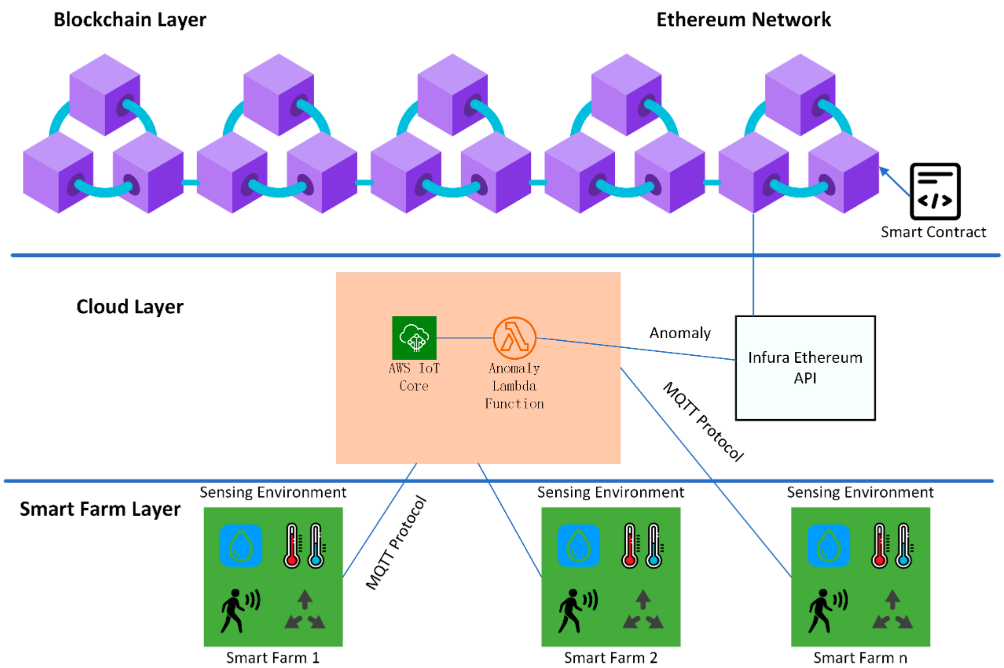


**Figure 10.** Blockchain cloud-based smart-agriculture application in [130].

Subsequently, the cloud layer is equipped with systems designed to perpetually monitor and process data from sensors to distill relevant insights. MQTT serves as a prevalent method for data transmission in discrete packets from source to destination. This paper introduces a lambda function within the AWS ecosystem, devised to interpret AWS IoT Core data, extracting pertinent information from connected agricultural sensors. The AWS IoT Core serves as a nexus for a multitude of IoT sensors within this smart agricultural setup. An efficient IoT messaging framework is imperative to accommodate various IoT communication protocols, like MQTT, ensuring data collection from a vast array of devices while optimizing for network throughput.

Upon identifying safety-related anomalies through lambda function analysis, a POST request is made to the Infura API, prompting updates on the Ethereum blockchain. Such updates may encapsulate irregular sensor readings and device statuses, among other data points. The Infura API, serving as an Ethereum blockchain interface, facilitates the execution of smart contracts and transactional operations on Ethereum nodes.

The concluding layer, the blockchain layer, is characterized by a decentralized assembly of Ethereum nodes managed and mined by entities utilizing Ethereum's comprehensive nodes. Infura administers these nodes and offers an API for transactional updates within user accounts, ensuring that modifications are propagated across the Ethereum network.

In essence, data collection is executed via sensor kits, with anomalies securely recorded on the blockchain through Ethereum smart contracts. This mechanism not only enables real-time updates and management of safety incidents but also fosters information exchange among agricultural communities via blockchain, enhancing the collective defensive posture of the system. Furthermore, the paper contemplates the adoption of advanced blockchain technologies to augment the efficacy and scalability of this solution.

Paper [131] proposes a blockchain technology-based solution to tackle data security and privacy challenges in smart agricultural systems employing IoT. Particularly in agricultural IoT applications, the expanding number of devices escalates the difficulty of ensuring data security and privacy. These systems amass and analyze vast quantities of sensitive information, including soil moisture levels, temperature readings, and light intensity. However, conventional security strategies frequently fall short of addressing the increasing security risks. Consequently, ensuring the IoT devices and their data remain secure is of utmost importance.

The paper recommends incorporating blockchain technology into the IoT security framework to overcome these obstacles. Blockchain's fundamental features, such as immutability and transparency, enhance the system's security, data integrity, and reliability. In the proposed structure, only verified devices and users can interact with data, significantly reducing the potential for breaches and unauthorized access. Moreover, the decentralized nature of blockchain enhances the system's robustness and its resistance to cyber threats by reducing the potential for single-point failures. This innovative approach delineated in the paper effectively navigates the complex landscape of security management for IoT in smart agricultural settings.

Table 5 provides a summary of different research areas and their applications as explored in the literature pertaining to ensuring system security.

**Table 5.** Ensuring system security related papers.

| Targeted Challenges | Papers | Short Introductions | Blockchain-Enabled Opportunities |
|---|---|---|---|
| Ensuring System Security | [120] | This paper introduces a system that combines IoT and blockchain technology, designed to improve farm surveillance and productivity with minimal human intervention. | Blockchain technology in this context ensures data integrity and security for the IoT systems in agriculture, enabling reliable and tamper-proof record-keeping. |
| | [121–123] | IoT, widely applied in the past decade, focuses on connecting smart devices via wired or wireless networks for real-time communication, processing, and monitoring of diverse scenarios, but its heterogeneous and resource-constrained devices challenge traditional security protocols. | Blockchain technology is increasingly being embraced in multiple industries as an innovative approach to secure IoT systems. This adoption addresses the shortcomings of conventional protocols in managing the diverse and resource-limited nature of IoT devices. |

**Table 5.** *Cont.*

| Targeted Challenges | Papers | Short Introductions | Blockchain-Enabled Opportunities |
| --- | --- | --- | --- |
| | [124] | Introduced a framework that merges blockchain and IoT technologies to address consumer trust concerns in managing risks associated with agricultural production. | By utilizing blockchain technology, significant improvements in trust and security have been achieved in agricultural IoT data sharing. |
| | [125] | The article introduces SP2F, a framework designed to enhance security and privacy in smart agricultural UAVs by addressing cyber-attacks and data privacy threats through the integration of blockchain and deep learning technologies. | Utilizing blockchain technology, the SP2F framework provides decentralized data authentication and a strong defense against data poisoning and inference attacks within IoT-enabled smart agriculture. |
| | [126,127] | The IoT field faces major attacks like interference, side-channel, malicious code injection, and rogue node insertion, highlighting the importance and complexity of securing IoT devices against vulnerabilities. | Blockchain technology, characterized by its distributed ledger and peer-to-peer networking capabilities, presents a resource-demanding but efficient strategy to improve the comprehensive security of IoT devices, even though direct integration poses challenges. |
| Ensuring System Security | [128,129] | DDoS attacks in IoT are a persistent threat due to the vast number of devices with low security, making them ideal for attackers to exploit and turn into botnets for launching attacks. | Blockchain provides a decentralized, tamper-resistant, and transparent mechanism for managing data, which enhances IoT security by bolstering device authentication, ensuring data integrity, and establishing a distributed defense system. |
| | [130] | The study introduces a security monitoring framework based on cloud and blockchain technologies for smart agriculture IoT applications. This framework improves security and efficiency through the use of Arduino sensor kits, AWS cloud services, and Ethereum smart contracts. | Utilizing the decentralized, transparent, and immutable characteristics of blockchain, the suggested framework markedly improves the security and dependability of IoT in smart agriculture. It enables real-time detection of anomalies and supports communication across the community. |
| | [131] | The paper proposes a secure system for smart agriculture, combining IoT, blockchain, and edge computing, focused on improving data privacy and security within agricultural IoT environments. | Blockchain technology in the system ensures data integrity and secure access, offering a decentralized solution to IoT security challenges in agriculture. |

The table highlights key studies that address IoT security challenges using blockchain. It showcases how blockchain enhances data integrity, authentication, and protection against threats like rogue node injections and DDoS attacks. The studies also demonstrate innovative solutions, such as integrating blockchain with cloud computing, to improve security in agricultural IoT systems.

Advantages:

Integrating blockchain with IoT offers several advantages for agricultural operations, enhancing security, transparency, and adaptability. Blockchain's tamper-proof ledger strengthens IoT security by enabling robust authentication, ensuring data integrity, and protecting against threats such as data poisoning or rogue node injections, as demonstrated in studies [120,124,125]. Moreover, smart contracts and decentralized architectures [130,131] facilitate improved transparency and automation, enabling real-time monitoring with reduced manual intervention and providing clearer audit trails. Additionally, blockchain solutions prove adaptable to the diverse and resource-constrained nature of IoT devices, offering secure and standardized protocols to address heterogeneity, as noted in [121–123]. These benefits make blockchain an invaluable tool for advancing the efficiency and reliability of IoT systems in agriculture.

Disadvantages:

Implementing blockchain in IoT systems for agriculture faces several challenges, particularly resource and cost constraints, as significant computing power and storage demands can strain small-scale or low-power IoT devices [121–123]. Scalability and performance bottlenecks also pose issues, with high data throughput and frequent transactions potentially overwhelming current blockchain frameworks hindering real-time agricultural applications. Additionally, the deployment and integration of smart contracts, cloud services, and IoT sensors ([126,127]) add considerable complexity, making it difficult to maintain interoperability and security across multiple platforms.

Best Results:

Recent studies demonstrate significant advancements in integrating blockchain with IoT to address security and trust challenges in agriculture. Robust security frameworks, ranging from UAV-focused solutions [125] to end-to-end monitoring platforms [130], show how combining blockchain, deep learning, and cloud computing can substantially enhance IoT security. Additionally, research [124,128,129] highlights blockchain's effectiveness in mitigating DDoS attacks and preventing data tampering, fostering greater trust in shared agricultural IoT data. Practical proof-of-concept implementations [120,130,131] further validate these technologies, showcasing prototypes that improve surveillance, privacy, and reliability—key enablers for scaling these systems across broader agricultural applications.

Overall, these papers underscore blockchain's potential to secure and optimize IoT-based agricultural applications while acknowledging that issues of scalability, resource constraints, and complex integration still need further exploration.

## 5. Future Research Directions

In this chapter, we present possible future research directions that build on both our own analysis and the findings reported in the literature. Specifically, these directions arise from gaps identified in previously published research and from our observations throughout our study. While our team proposes some of these directions as avenues for our own future work, other directions are recommendations that can be pursued by researchers in the broader academic and industry communities. By providing a detailed overview of these potential paths, we hope to spark additional discussions and encourage further investigations that will advance the development and application of blockchain technology.

### *5.1. Improving the Scalability and Performance of Blockchain*

Enhancing blockchain's capability to efficiently handle voluminous agricultural IoT data hinges on implementing a multi-layered architectural design. This design stratifies the system into distinct segments: smart agriculture, smart contracts, data storage, and user access. Such segmentation facilitates more efficient operation and scalability of the overall system. Integrating IoT with blockchain technology promotes superior data collection and management, strengthening both data security and transparency.

The use of smart contracts to automate data processing workflows significantly reduces the reliance on manual intervention, thereby enhancing the system's operational efficiency and responsiveness. Moreover, adopting strategic approaches to data handling, such as data compression and selective storage, alleviates the load on the blockchain. These optimizations enable the system to manage large datasets effectively, tailoring blockchain functionality to better address the unique demands of agricultural IoT while maintaining robust scalability.

While blockchain technology presents promising solutions for enhancing transparency and traceability in agricultural and livestock supply chains, its practical implementation faces several challenges. Scalability remains a key concern, as current blockchain architectures often struggle with the high transaction volumes required in large-scale supply chain operations. Additionally, the energy-intensive nature of consensus mechanisms, particularly proof-of-work, raises significant environmental and economic issues.

Effective implementation also demands extensive collaboration among stakeholders, including farmers, distributors, and regulators. Achieving consensus and fostering trust among these diverse groups can be particularly challenging in fragmented industries like agriculture. Addressing these complexities requires innovative solutions, such as transitioning to energy-efficient consensus mechanisms and developing incentive structures to promote stakeholder engagement.

By tackling these trade-offs, blockchain technology can better meet the demands of real-world applications, providing a more balanced perspective on its limitations and potential areas for improvement. This approach underscores the practicality of blockchain adoption while identifying avenues for further refinement and development.

### *5.2. Optimizing Blockchain Storage and Redundancy Issue*

Addressing the challenges of storage and redundancy in blockchain entails implementing effective data processing and storage strategies. Among these strategies, data pruning, layered storage, and sidechain technologies stand out as prevalent solutions. Data pruning involves trimming unnecessary old blocks or transaction records from the blockchain, reducing its storage demands while preserving its integrity and security. This method is instrumental in eliminating redundant data that no longer serves a purpose.

The layered storage strategy mitigates the storage burden on individual nodes by dispersing data across nodes at various hierarchical levels. This strategy allows for the decentralized nature of blockchain to be maintained while effectively managing the scale and cost associated with data storage.

Sidechain technology functions by establishing auxiliary chains that run parallel to the main blockchain. These sidechains are designated for specific transaction types or data categories, enabling the diversion of certain workloads from the main chain. This not only enhances the processing capacity of the main chain but also contributes to a reduction in its storage requirements.

Integrating these technological solutions enables blockchain systems to significantly curtail the space needed for data storage and minimize redundancy without compromising on essential attributes like decentralization, security, and immutability. This optimization is particularly vital in scenarios involving extensive data management, such as in agricultural IoT applications. These advancements facilitate a more efficient processing and storage of data within blockchain systems, concurrently lowering maintenance costs and augmenting overall system performance. Exploring these optimizations represents a promising avenue for further research in blockchain technology.

### *5.3. Integrating Blockchain with Other Technologies*

Combining blockchain with AI and cloud computing is poised to dramatically transform the management of agriculture and livestock sectors. Blockchain's robust framework for data management, characterized by its security, transparency, and immutability, is pivotal in ensuring the reliable storage and tracking of critical information such as production data, supply chain details, quality control, and sales data in these sectors. When integrated with big data analytics, this repository of information can be processed into valuable insights, facilitating informed decision-making.

Furthermore, utilizing AI and IoT technologies enables continuous monitoring of variables like crop growth conditions, soil quality, and livestock health, allowing for adaptation to climatic changes. Leveraging cloud computing's powerful computational abilities, vast quantities of data collected can be swiftly analyzed to forecast trends, anticipate yields, and preempt disease outbreaks.

Blockchain enhances transparency and traceability in supply chain management, which is vital to food safety and quality. Combining AI with big data analytics further optimizes logistics, predicts market demands, and reduces waste. Additionally, smart contracts automate the execution of contract terms, streamline transactions like payments and insurance claims, and diminish the risks associated with human error and fraud.

This holistic approach, integrating multiple technologies, not only elevates production efficiency and product quality in agriculture and livestock but also fosters sustainable development. It contributes to reinforcing global food security and elevating the transparency and reliability of supply chains. As technology evolves, the future landscape of agriculture and livestock is set to become increasingly smart, efficient, and eco-friendly.

### 5.4. Optimizing Smart Contract Efficiency

Enhancing blockchain system efficiency requires optimizing smart contracts. Firstly, the design of smart contracts should focus on efficiency and simplicity to avoid complex logic and unnecessary data storage. For example, it is possible to design contracts that can be deleted or updated. Such contracts allow updates or removals without affecting the immutability of the blockchain, thus reducing the need for long-term data storage. Secondly, the execution efficiency of smart contracts can be improved through various optimization techniques. For example, adopting deferred or on-demand computation strategies, which execute computation-intensive operations only when necessary, not only reduces the resources needed for contract execution but also lowers the pressure on the blockchain network.

Furthermore, specific parts of the contract logic can be executed utilizing state channels or sidechain technologies. These innovations enable the performance of certain contract segments off the main blockchain network, with outcomes relayed back to the main network at pivotal moments. This strategy significantly reduces the burden on the main chain, thereby improving the network's overall efficiency. Additionally, adopting a modular approach to smart contract design facilitates their reuse across different contexts, enhancing development productivity while minimizing the duplication of code. Another critical aspect of smart contract optimization involves bolstering security measures. Employing advanced encryption methods and conducting rigorous security audits are critical measures for mitigating contract vulnerabilities and protecting against security risks, ensuring the blockchain system's integrity and the security of user assets. In essence, optimizing smart contracts in terms of design and execution can reduce unnecessary data storage on the blockchain, thereby improving the efficiency and security of contract operations and significantly improving the blockchain system's performance and user experience.

## 6. Conclusions

This paper explored how blockchain and the Internet of Things (IoT) can address key challenges in agriculture and livestock, including data security, transparency, and reliability. We began by outlining the principles of both technologies, underscoring their complementary nature in real-world farming contexts. By examining issues such as unclear product origins and vulnerable IoT devices, we highlighted the urgent need for secure, transparent solutions.

We identified four main areas of blockchain application—data management, supply chain traceability, smart contracts, and security—showing how distributed ledgers can validate sensor data, automate operations, and build trust among stakeholders. While these advancements hold promise, they also face obstacles like regulatory constraints, resource limitations, and network scalability. Future work should focus on designing domain-specific consensus mechanisms, balancing centralized and decentralized frameworks, and integrating AI-driven analytics. Tackling these challenges will integrate blockchain's core advantages—immutability, trust, and decentralized security—more deeply into agricultural IoT, ultimately enhancing efficiency, resilience, and sustainability in food systems.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| IoT | Internet of Things |
| AI | Artificial Intelligence |
| UAV | Unmanned aerial vehicle |
| GPS | Global Positioning System |
| HTTP | Hypertext Transfer Protocol |
| MQTT | Message Queuing Telemetry Transport |
| PoW | Proof of Work |
| DDoS | Distributed Denial of Service |
| API | Application Programming Interface |
| PoS | Proof of Stake |
| DPoS | Delegated Proof of Stake |
| PBFT | Practical Byzantine Fault Tolerance |
| PoA | Proof of Authority |
| RFID | Radio Frequency Identification |
| ECC | Elliptic Curve Cryptography |
| QR Codes | Quick Response Codes |
| AWS | Amazon Web Services |

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