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Designing an Efficient Blockchain-Enabled Internet of Things (IoT) framework for Smart Farming

Tsegazewold Kinfu[1], Yirga Yayeh[2], Yechale Amogne[3], Emiyamrew Azmeraw[4], A. O. Salau[5]

[1] Electrical and Computer Engineering, Hawassa University Institute of Technology(HUIoT), Hawassa, Ethiopia
[2] Department of Information Technology, Injibara University, Injibara, Ethiopia, National Yang Ming Chiao Tung University, Taiwan
[3] Electrical and Computer Engineering, Woldia Institute of Technology(WiT), Woldia, Ethiopia
[4] Computer Engineering, University of Gondar, Gondar, Ethiopia
[5] Department of Electrical/Electronics and Computer Engineering, Afe Babalola University, Ado Ekiti, Nigeria
tsegazewoldkinf@gmail.com, byyirga@gmail.com, yechaleamogne12@gmail.com, emigebreal19@gmail.com, ayodejisalau98@gmail.com

Abstract:

In recent years, the adoption of emerging technologies in developing countries has increased significantly, driving the growth of smart farming and precision agriculture. One of the most promising approaches involves the integration of blockchain-enabled Internet of Things systems to enhance security, transparency, and efficiency in agricultural operations. This study presents a four-layer architecture for a blockchain-based Internet of Things system in the domain of smart farming. The architecture consists of device nodes, fog nodes, a cloud server, and end users. The blockchain framework is implemented using Hyperledger Fabric, which ensures permissioned access and secure data management. To further strengthen system security, Role-Based Access Control is integrated. The system's performance is evaluated using metrics such as throughput and latency to measure efficiency and responsiveness. The results highlight the advantages of combining Hyperledger Fabric with a permissioned blockchain structure, offering improved security, reliability, and trust in agricultural data handling. This work provides practical insights for farmers, developers, and policymakers seeking secure and dependable Internet of Things solutions to support modern agricultural practices.

Keywords: Blockchain Network, Cloud Computing, Consensus Algorithm, Fog Computing, Hyperledger Fabric

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1. Introduction

Agriculture remains a foundational sector for global economic development, particularly in developing countries. It plays a vital role in ensuring food security, contributing to gross domestic product (GDP), and supporting rural livelihoods. According to recent data, a significant portion of the global population, especially in emerging economies, relies on agriculture as a primary source of income; indeed, the agricultural sector employed 892 million people worldwide in 2022, corresponding to 26.2 percent of total global employment [1], [2]. This reliance is especially pronounced in developing regions, as the share of employment in agriculture in 2022 was highest in Africa at 48 percent, while it was lowest in Europe at 5 percent [1], [3]. Emerging technologies must be applied in the agriculture sector in order to meet productivity and growth. Agriculture is currently ongoing a fourth revolution (farm 4.0) by integrating Wireless sensor networks (WSN), Artificial Intelligence (AI), Robotics, Unmanned Aerial Vehicles (UAV), Big Data Analysis (BDA), and Machine Learning [4]. The Internet of Things (IoT) is playing a crucial role in agricultural parameters to increase crop yields, decrease costs, and optimize sensor input data for activities like crop growth status, irrigation, monitoring livestock, soil condition, pesticide and fertilizer, weed control, and so on [4], [5].

In precision agriculture, artificial intelligence and machine learning are used to predict the content of the soil, crop rotation, planting time, and harvesting time by the use of agricultural sensors. Smart irrigation based on the Internet of Things (IoT) is also crucial to overcome the scarcity of clean water resources required for many plant varieties and achieve optimal water use in smart farming [6]. Although there are several issues and challenges with IoT and WSN mostly in terms of security and privacy, in smart farming and precision agriculture, recently Blockchain has been introduced to address the challenges and issues [7].

Blockchain technology was introduced in 2008 by the pseudonymous developer "Satoshi Nakamoto" as a decentralized ledger system designed to facilitate peer-to-peer transactions without the need for a trusted third party, such as banks. Initially, blockchain was primarily associated with cryptocurrency applications, particularly as the foundational technology behind Bitcoin [8]. Owing to its key characteristics—such as decentralization, transparency, immutability, and secure data handling, blockchain technology has expanded into various sectors beyond finance, including agriculture, healthcare, energy systems, and electronic voting [8], [9]. In permissioned blockchain platforms like Hyperledger Fabric, which are particularly well-suited for Internet of Things (IoT) environments, transaction overhead is significantly reduced due to the absence of public mining and associated fees. This makes blockchain a viable option for secure and efficient data exchange in smart farming and other IoT-based applications.

Every user has their unique address which is protected with the help of public-key cryptography [8]. IoT plays a vital role in social and national development by enabling interconnections between humans and computers, humans and smart devices,and computers to computers. This interconnectedness allows for ubiquitous access to information and services. IoT devices are being widely adopted in various industries, including transportation, agriculture, home automation, and health monitoring through wearable technology. These devices improve quality of life, enhance safety, reduce workload, and enable effective monitoring and management of agricultural fields. The key components of IoT devices include sensors, devices, gateways, and cloud infrastructure [10]. However, maintaining and securing IoT deployments in centralized cloud server farms can be challenging. Blockchain and IoT are two revolutionary technologies and combining both is seen as a possible solution to the problem of privacy and security of the IoT devices. Blockchain technology enables secure and decentralized transactions, making it suitable for various applications such as cryptocurrency-based financial transactions, token-based protocols, self-sovereign identity standards, global supply chain management and tracking, as well as digital energy and smart grid systems.

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In the context of Ethiopia, farmers primarily rely on traditional farming techniques. However, these methods often struggle to achieve higher crop yields and improve overall quality of life. To address this issue, blockchain-based IoT plays a crucial role in enhancing productivity within smart farming through the implementation of secure, real-time, and efficient monitoring systems. Therefore, designing a blockchain-based IoT system for smart farming becomes essential. Ultimately, our contributions to this paper are as follows:

- We proposed a four-layer blockchain-based IoT architecture, including device nodes, fog computing, cloud servers, and end users, tailored for smart farming environments.
- We implemented Role-Based Access Control (RBAC) within the Hyperledger Fabric framework to ensure secure and permissioned data management.
- We designed and tested chaincodes for monitoring crop and livestock data, enabling efficient and tamper-proof smart farming operations.
- We addressed IoT device limitations by leveraging fog computing for real-time data processing and cloud servers for additional storage, ensuring scalability and low latency.
- We evaluated the proposed architecture through performance metrics such as throughput and latency, demonstrating its capability to operate efficiently in real-time agricultural scenarios.

2. Literature Review

2-1- Blockchain Overview

Blockchain technology was invented by Satoshi Nakamoto in 2008 as a decentralized public ledger to support the decentralized peer-to-peer transactions [8]. It came into the limelight as the backbone to cryptocurrencies such as Bitcoin and other blockchain applications. In its simplest terms, blockchain can be described as a shared database that stores transaction records in blocks that have a timestamp. To provide an efficient way of storing data, each block within a blockchain is made of its hash and that of the previous

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block, a time stamp, and data about the transaction hence making it difficult for anyone to manipulate or forge the data stored in the block chain as shown in Fig. 1 [11], [12]. Each block unit consists of a block header and a block body. Especially, the block header involves six components:

- Block version is a software version number indicates which con- sensus protocol to follow.
- Markle Tree Root Hash is used to verify the hash code that identifies all block transactions.It recursively defined as a binary tree of hash codes.
- Timestamp is given in seconds since 1/1/1970. It is used to immutably track the creation and update time of the block for block integrity guarantee.
- N-Bits identifies the target threshold of hash code that specifies the valid block.
- Nonce is an arbitrary number that can be used just once in a cryptographic communication. It is 4-byte field, which usually begins with '0s' and grows for every hash computation.
- Parent Block Hash is a 256-bit hash code that refers to the previous block. Without this component, there would be no connection and chronology between blocks in the blockchain.

Blockchain technology is defined by several key characteristics [13]–[15]: Decentralization distributes control across a network of nodes, enhancing security and privacy. Transparency allows full visibility of transaction histories, while Autonomy eliminates intermediaries using cryptography and consensus mechanisms. Security is ensured through asymmetric cryptography, and Immutability guarantees that recorded data cannot be altered. Traceability tracks data origins and changes, ensuring compliance, while Anonymity protects user privacy. Integrity is maintained through an immutable ledger, Fault tolerance ensures system reliability, and Automatic functions like smart contracts enable self-executing processes. These features make blockchain secure, transparent, and efficient.

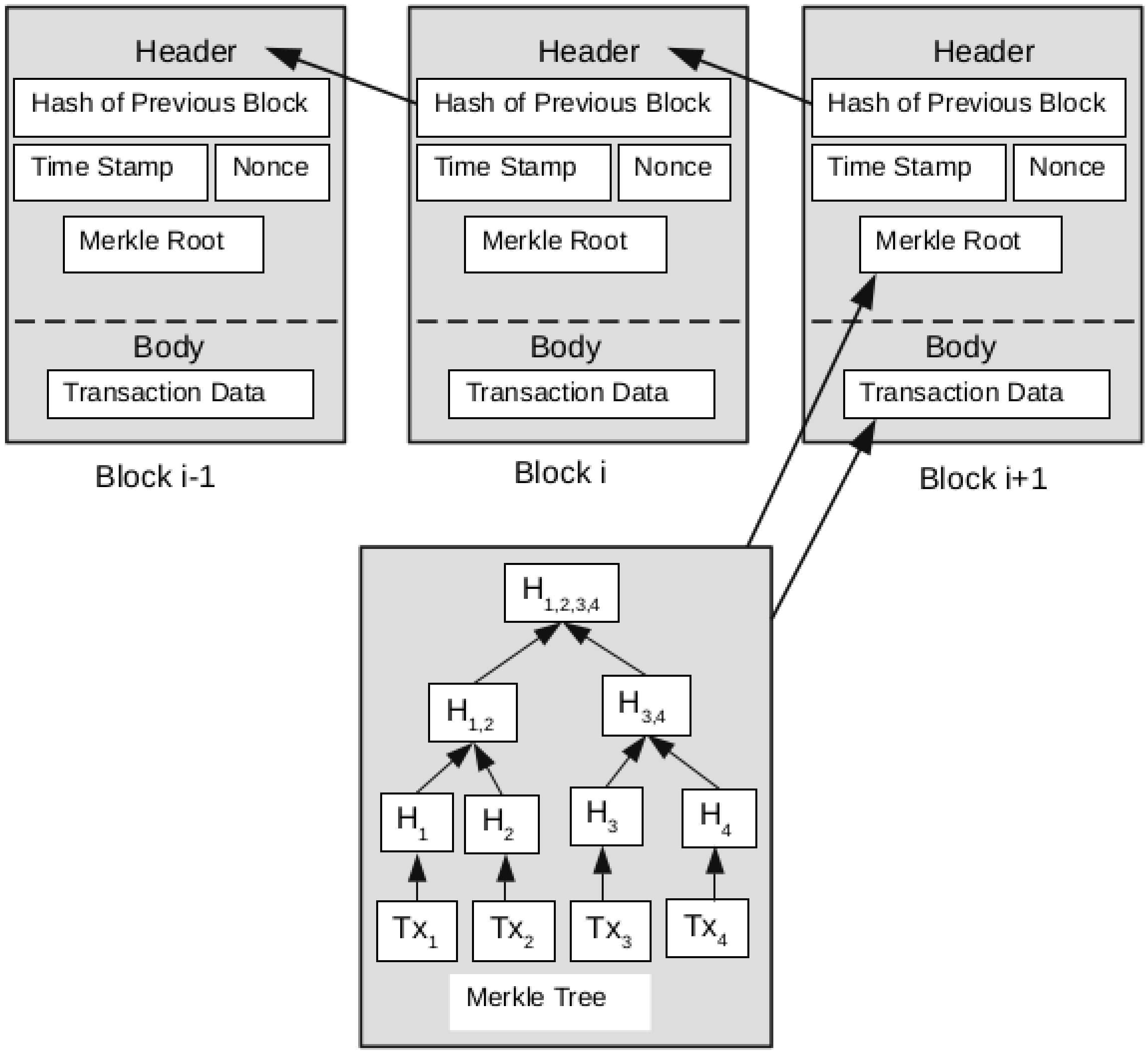

Fig. 1: Sequence of hashed blocks in Blockchain

The Consensus Algorithm is a mechanism that ensures all nodes in a blockchain network agree on the current state of the blockchain [16]–[18]. It validates transactions and guarantees that all participants maintain identical copies of the blockchain, enhancing security and integrity. Common consensus algorithms include Proof of Work (PoW), where nodes compete to solve complex computational problems, ensuring transaction verification but consuming substantial resources. Proof of Stake (PoS), an energy-efficient alternative, selects validator nodes based on the amount of cryptocurrency they hold, though it risks centralization by favoring wealthier nodes. Practical Byzantine Fault Tolerance (PBFT) requires a majority of authority nodes to approve a block, commonly used in permissioned blockchains like Hyperledger. Another notable protocol is RAFT, which simplifies consensus in permissioned networks by selecting a leader node to validate transactions, providing efficient ault tolerance with less resource consumption. Each algorithm addresses different trade-offs in terms of energy efficiency, decentralization, and fault tolerance, making them suitable for varying blockchain use cases. Some of the uses of blockchain other than being used to supports cryptocurrencies are in the healthcare sector, supply chain, and agriculture among others. The fact that Hyperledger Fabric is able to offer these means, its capacity for providing tamper-proof records and maintaining transparent operations has brought benefits especially where high levels of trust and integrity are needed. For instance, using blockchain boosts IoT networks' security, conveying privacy and storage challenges; blockchain is effective within smart farming and precision agriculture.

2-2- Integration of Blockchain and IoT in Smart Farming

The Internet of Things (IoT) is increasingly recognized for its transformative potential in diverse sectors such as agriculture, healthcare, and industry. IoT connects humans to computers, smart devices, and even other computers, allowing everything to be linked to the internet or a network, accessible anytime and anywhere. This interconnectedness is already having a significant impact in sectors like transportation, health monitoring, home automation, and, notably, agriculture. The primary goal of IoT is to enhance life quality, improve safety, simplify workloads, and help monitor or manage various environments. Core components of IoT devices include sensors, devices, gateways, and cloud infrastructure [6]. When IoT is integrated with blockchain technology, it takes security and privacy to the next level by decentralizing data storage and removing the need for centralized servers. Blockchain secures data with cryptography, ensuring that it is nearly impossible for unauthorized entities to tamper with or access it. Additionally, blockchain provides a transparent and immutable transaction history, reinforcing data integrity and accountability. With the use of smart contracts, agreements between IoT devices can be executed automatically without intermediaries. For farmers, integrating IoT into their farming practices opens up new opportunities to monitor and improve crop, plant, and livestock quality. By using IoT-enabled software on devices like smartphones, tablets, or computers, farmers can monitor soil conditions, irrigation systems, pest control, and other key activities remotely. This technology can significantly enhance the agricultural supply chain, improving its efficiency and predictability, as every step of the process can be monitored and validated.

A blockchain-based smart farming system consolidates agricultural data on a single, integrated platform [3]. Blockchain ensures that this data is securely stored, tamper-proof, and transparent. Through a combination of cryptographic methods and consensus mechanisms, blockchain guarantees the authenticity of data before it is recorded. The immutability of blockchain ensures that data remains trustworthy, traceable, and easily accessible in the future, making it a valuable asset in farming. The predictability introduced by blockchain also reduces uncertainty in agricultural output, leading to better profitability and less waste of resources.

The integration of Internet of Things and blockchain technologies in agriculture removes the reliance on trusted third parties, enabling all stakeholders to benefit from a transparent and secure system [19]. IoT devices, equipped with sensors, collect data throughout the farming process. For instance, information about product name, origin, and production logs are captured at the manufacturing stage, and growth data is continuously recorded as the product evolves. Blockchain plays a crucial role in securely storing this data, while also managing encryption, decryption, and verification. Smart contracts streamline the process by automating tasks at specific times, improving scalability, and reducing costs [19].

2-3- Related Work

In this section, we discuss and present related work that has been done previously in the field of blockchain based IoT in smart farming. Torky, M., and Hassanein, A. E [19] pointed out the opportunities, challenges, and issues of blockchain integrated with IoT in precision agriculture and they proposed a novel blockchain model to mitigate the drawbacks of IoT sensor devices implementation in smart farming. The agricultural data are transacted in a secure and efficient manner by using a blockchain distributed ledger. Furthermore, they figured out the challenges blockchain to deploy in smart farming with regarding to security, power consumption, storage devices, latency and throughput.

Hang et al. [20] proposed that blockchain based secure fish for the integrity of agricultural data. To be more precise, the proposed architecture has conceptualised four sub-systems which include fish farm, the blockchain network, data storage and the end-user. The fish farming realm has been developed with real-time monitoring and management system by employing various kind of sensors such as temperature sensor, water level sensor, oxygen sensor, PH sensor etc and the actual controllers which control the environment of fish farming such as water pump, pond heater, fish feeder light LED etc have been incorporated control by sensing the environment via the sensors. Peer-to-peer data transaction between the end-users and devices is held by using a blockchain network. Blockchain network interconnected to fish farm environment and the sensors and the actuators exchange information in a fish farm in order to build complete fish farm legacy. They proposed a permissioned blockchain network to overcome the privacy data exposure and to ensure authorization and authentication. However, they didn't consider the performance metrics of latency and throughput of the blockchain network.

Hu et al. [21] suggested the solution of blockchain based edge computing that can eliminate the trust exposure of the organic agricultural supply chain.The characteristics of Organic Agricultural Supply Chain are of centralization monopoly and asymmetric type. In case of lack of transparency, the Organic Agricultural Supply Chain leads to trust disclosure of customers. The authors presented Ethereum based blockchain integrated with Edge Computing in order to manage the trust of diverse architecture and computing models in a distributed manner. The stakeholders (such as users and providers, IoT data sources, software components, fog nodes and cloud storage) are maintained by their own blockchain services. They introduced a consensus algorithm to improve the performance and the costs have been declined when compared to the traditional consensus algorithm. Salah et al. [9] proposed blockchain based soybean traceability to ensure the safety of agricultural products and food supply chain. The traceability and tracking of soybean has been performed effectively by using the Ethereum based blockchain and smart contract. Their system enhanced the efficiency and safety of soybean traceability with high integrity, security, and reliability. The blockchain distributed ledger recorded and stored all transactions in a decentralized file system.

Vangala et al. [3] suggested comprehensive literature on smart secure sensing for blockchain based IoT in agriculture. The paper provides information security of sensing devices by integrating blockchain and IoT in smart farming. They figured out what is the security threats in smart farming, how could enhance the

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security of the data by using blockchain technology, and what is the drawbacks of Blockchain based IoT in smart farming.

Patil et al. [22] proposed a framework for lightweight blockchain based secure smart greenhouse farming. It comprises four sub-components (for instance, smart greenhouse, overlay network, cloud storage and end user). The security framework in this works in the physical layer, the communication layer, the database layer, and the interface layer to address the security and privacy threats of IoT nodes. While, they didn't point out the throughput and latency challenges in blockchain network.

Kafhali et al. [23] proposed an architecture for controlling the IoT data through the help of the blockchain and fog computing to manage internet of things (IOT) issues with reference to multiple accessibility of devices. The fog computing layer sensitive data can be accessed locally and there is no need to send it to the cloud layer. The edge node acquire, manage and monitor the IoT devices that gather, process and store the information. For the management of resources required for the implementation of the SDN and NFV, they are interfaced into the system.

Friha et al. [24] suggested the deployment of a well-developed security framework with the help of blockchain and SDN for fog computing in agriculture internet of things. The proposed security architecture is composed of three main parts: for example an IoT data management system for agriculture, a blockchain integrity monitoring scheme and a virtual switch software for software defined networking technologies for the enhancement of network management.

The proposed system has been designed by using private or permissioned blockchain in order to mitigate the latency and throughput challenges of public or permission less blockchain. The private blockchain is designed for private organization and the users have to be authenticated and authorized by the organization

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admin to access the blockchain. So, in smart farming there are different wireless sensors to automate the farming land and the sensors data transaction takes place by using blockchain technology.

3. Research Methods

3-1- Overview

In this section, we present the overall design principles and techniques used to integrate blockchain and IoT technologies in the context of smart farming. The proposed system is specifically designed to address key challenges associated with blockchain-IoT integration in agriculture, including issues related to throughput, latency, data privacy, and security. To implement the system, a private blockchain is utilized, leveraging the Hyperledger Fabric framework. The proposed architecture comprises four main components, as illustrated in Fig. 2 farming sensor nodes, the fog computing layer, the cloud computing layer, and end users.

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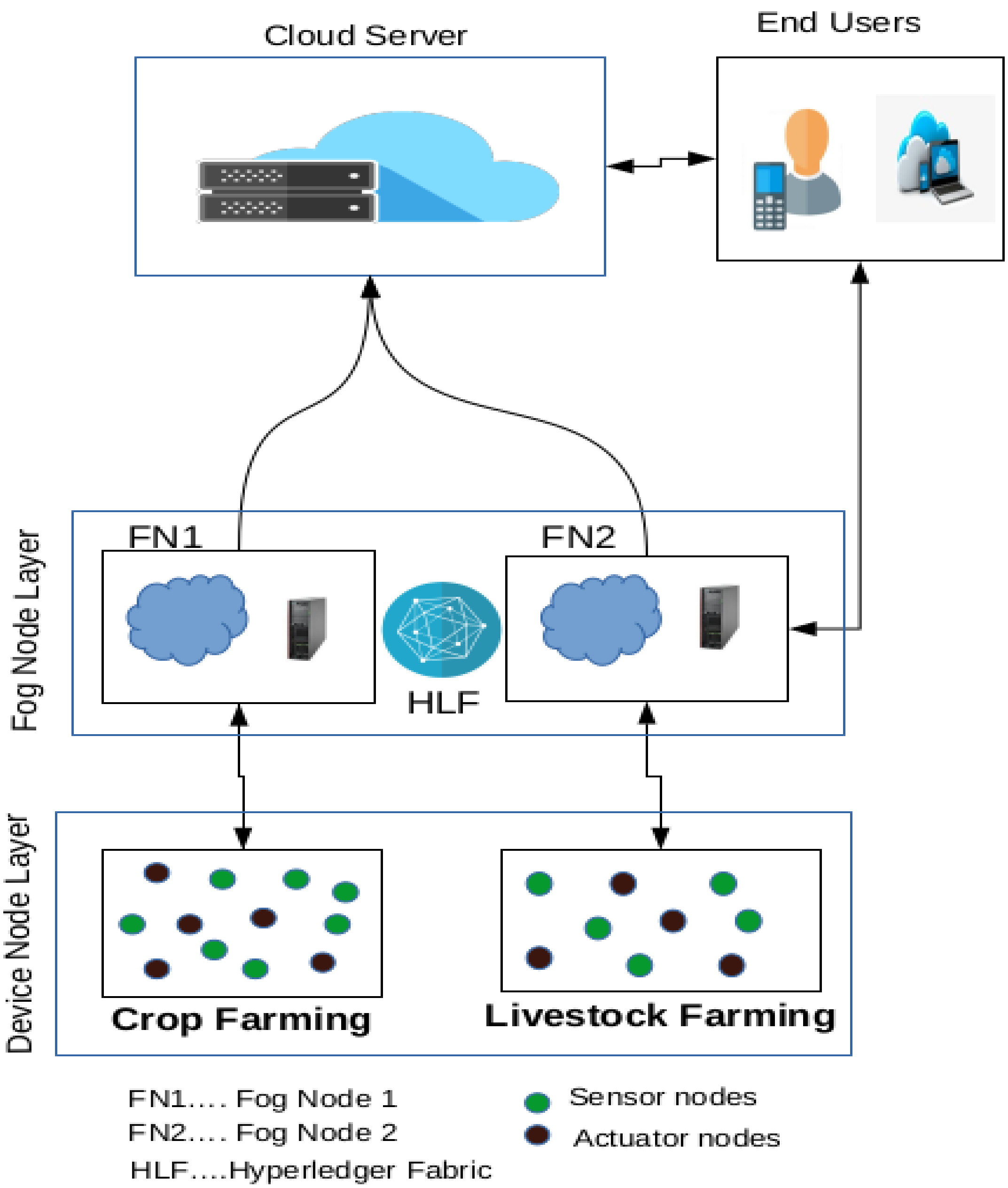

Fig. 2: A proposed framework

3-2- Farming Device Nodes

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Farming device nodes are an important component of the proposed framework for blockchain-based IoT in smart farming. These nodes are designed to automate farming operations and optimize crop and livestock yields. There are two types of device nodes, one for crop farming and the other for livestock farming. The crop farming device nodes can be equipped with a variety of sensors and actuators that can help optimize irrigation, fertilization, ventilation, and heating systems. For example, sensors for measuring soil moisture, temperature, and nutrient levels can be used to automate irrigation and nutrient delivery, while actuators such as water pumps and valves can be used to control irrigation systems. Similarly, sensors for measuring air temperature and humidity can help optimize ventilation and heating systems, while actuators such as fans and heaters can be used to control these systems.

The livestock farming device nodes can also be equipped with sensors and actuators that can help optimize ventilation, feeding, and watering systems. For example, sensors for monitoring water and feed consumption, as well as animal behavior, can provide insights into the health and well-being of livestock. Actuators such as feeders and water dispensers can be used to automate feeding and watering systems.

In the proposed system for blockchain based IoT in smart farming, MQTT is used as the communication protocol between the sensor nodes and the fog nodes. This protocol is simple and efficient in that it meets the requirements of the IoT devices that are limited in terms of resource. Most of the IoT devices are constrained in bandwidth and power so MQTT is a light weight publish/subscribe messaging protocol. The fact of usage of MQTT allows implementing effective and high quality exchange between the sensor nodes and fog nodes, with probe overhead and low latency levels. The MQTT protocol allows for secure communication through the use of Transport Layer Security (TLS) and user authentication, ensuring that only registered and authorized devices can communicate with the fog nodes.

For security purposes, each sensor node is registered in the HLF blockchain network. This ensures that only registered sensor nodes can send sensor data to the fog nodes, and helps prevent unauthorized access to the

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network. The RBAC (Role-Based Access Control) is also used to manage access to the data stored on the Hyperledger Fabric blockchain network, ensuring that only authorized users can access and modify the data.

By integrating these sensors and actuators with the fog nodes and HLF blockchain network, you can create a real time monitoring and control system for your crops and livestock. The fog nodes can analyze the data generated by the device nodes and store it on the HLF blockchain network, ensuring that the data is secure, transparent, and immutable. This can help with compliance and auditing requirements, and also enable end users to access the ledger data to get updated sensor data.

Various types of sensors are used in precision agriculture to measure different parameters. Temperature sensors can measure soil, plant and air temperatures, which are important to control soil processes, plant growth, and root growth, as well as to predict crop yield. Humidity sensors are used to measure humidity and air temperature, which can affect water regulation and gas exchange during plant photosynthesis. Soil moisture sensors determine the actual moisture content of the soil, which is essential in determining irrigation schedules. Soil pH sensors measure soil pH, which greatly affects nutrient availability and the presence of microorganisms in the soil, influencing plant growth. Nanobiosensors have immense potential in the agricultural field and can accurately detect various fertilizers, pesticides, and soil quality. Wind speed sensors are crucial in smart agriculture to assess wind speed and direction. Specialized monitoring devices, such as raindrop sensors, are needed to count raindrops due to unpredictable heavy rainfall caused by rapid climate changes. Droplet sensors can be used for the precise application of plant protection chemicals to avoid over-usage of pesticides, which can damage the crop and ecosystem.

3-3- Fog Computing Layer

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In 2014, Cisco introduced Fog computing to address the challenges of availability, latency, cost, and energy consumption that come with IoT design [25]. Fog computing is composed of numerous fog nodes, small, lightweight devices that offer computing, networking, and storage resources to complete tasks that end devices are unable to accomplish. Real-time analysis and latency-sensitive applications are run at this layer, and not all of the data gathered is transferred to the cloud for processing [24]. The fog node layer in our proposed architecture consists of fog nodes that process and aggregate data from edge devices in real time, store some data locally, and synchronize critical IoT data with the HLF blockchain network.

Fog nodes are responsible for managing devices, performing analytics, visualizing data, and communicating with edge devices and cloud layers for long-term storage or more intensive processing. The HLF blockchain network and smart contracts are deployed in this layer, making it feasible to access and store various sensor transactions. The fog nodes use Wi-Fi, Bluetooth, or Zigbee technology for connectivity, and fog-to-fog communication is possible in scenarios where a nearby fog infrastructure can perform tasks more efficiently and with less power consumption than sending them to the cloud layer.

In our implementation, Hyperledger Fabric components are deployed on fog nodes using Docker containerization. While fog computing may involve dedicated servers in some architectures, our approach uses containerized services on shared hardware to efficiently handle blockchain transactions, reduce latency, and improve energy utilization. The Blockchain Client runs within these containers creating transactions, batching them, and delivering them to the validator to be grouped into blocks and committed to the blockchain. The fog node layer thus remains a crucial component, offering computing and storage resources at the edge of the network, reducing latency and energy consumption, and improving the overall system efficiency.

3-4- Cloud Computing Layer

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The cloud computing layer in our proposed framework is responsible for long-term storage, intensive processing, and data analysis. This layer is composed of cloud nodes, which offer a scalable and flexible infrastructure to store and process large amounts of data generated by the IoT devices. In this layer, we have deployed a global HLF blockchain network, which stores the complete transaction history in a secure and immutable way. The cloud nodes are distributed across different geographical locations, which provides redundancy and mitigates the risk of single point failure. The cloud layer communicates with the fog node layer and edge devices for data processing and storage. The cloud nodes are connected through high-speed internet and can be easily scaled up or down based on the demand of the system. The cloud computing layer plays a crucial role in providing reliable, scalable, and secure storage and processing capabilities for the proposed framework.

3-5- End Users

The end users layer in the proposed framework consists of four main actors: farm admin, farmers, agronomist, and veterinarian. These actors have different roles in the smart farming ecosystem and are responsible for different aspects of the farming process. To access the data stored in the fog nodes and cloud server, the end users must first register to the HLF blockchain network. The registration process involves generating a public key and a private key using elliptic curve cryptography (ECC). The Fabric client provides the registered users with a signed certificate and stores their identity on their wallet.

Once enrolled, the end users can retrieve data from the fog nodes and cloud server. When they want real-time information about their farming field, they can directly access the fog node. In the HLF blockchain network, the end users can view and verify transactions related to their activities. The data in the blockchain network is immutable, ensuring that the end users can trust the data they retrieve. In addition, the end users can use smart contracts to automate their activities and reduce the need for manual intervention. For

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example, farmers may use smart contracts to manage their crop cycles, while veterinarians may use them to monitor animal health.

4. Blockchain Network

The integration of blockchain with IoT in smart farming addresses critical challenges such as data security, transparency, and decentralized data management. This section elaborates on how Hyperledger Fabric, a permissioned blockchain, is employed to provide secure and tamper-proof management of farming data, ensuring efficiency and trust within the farming ecosystem.

4-1- Fabric Transaction Workflow

The Hyperledger Fabric blockchain framework is selected due to its modular, permissioned architecture, which allows only authorized entities to participate in the network. The workflow of data transactions begins at the IoT device level, where farming data such as soil moisture, temperature, and livestock monitoring metrics are collected in real time. This data is sent to the fog computing layer, where it is processed and aggregated. Once processed, the data is transmitted to the cloud computing layer for storage and further analysis.

In the cloud, the data is integrated into the Hyperledger Fabric blockchain. Here, a transaction represents an event in the farming environment (such as a change in temperature or soil moisture), which is validated by the blockchain network before being recorded. The Fabric's transaction workflow follows these main steps:

- Transaction Proposal: The data is first proposed as a transaction to be added to the blockchain. The IoT device sends a request to the blockchain, which is processed by a set of peer nodes.
- Endorsement: The proposed transaction is simulated and endorsed by a predefined set of peers. These peers are responsible for executing the transaction logic (chaincode) without actually

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committing the results to the ledger yet. The endorsement ensures that the transaction complies with the blockchain's rules and policies.

- Ordering: After receiving the required endorsements, the transaction is submitted to the *ordering service*. This service groups multiple transactions into blocks, ensuring they are correctly sequenced and timestamped.
- Validation and Commitment: Once ordered, the block containing the transaction is sent to all peers for validation. Each peer checks the validity of the transaction (e.g., ensuring no conflicts with prior transactions) and appends the block to its local copy of the blockchain ledger.
- Final Storage: After validation, the transaction is permanently recorded on the blockchain. This ensures an immutable, auditable record of all farming-related events, allowing farmers and stakeholders to verify and trust the data.

The entire process from data collection to final storage on the blockchain happens in near real-time, ensuring that the system can handle the dynamic nature of smart farming operations. This guarantees transparency, as each transaction is traceable, secure, and immutable.

4-2- Blockchain Consensus Mechanism

Hyperledger Fabric uses a *RAFT consensus algorithm* to achieve agreement among distributed nodes on the blockchain. Unlike public blockchains that rely on computationally expensive methods like *Proof of Work (PoW)*, the RAFT consensus mechanism is specifically designed for *permissioned blockchains*, making it more efficient for enterprise-level applications like smart farming.

a) RAFT Consensus Overview::

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- Leader and Follower Nodes: RAFT operates by electing a leader node among the ordering service nodes (OSNs). This leader is responsible for managing the transaction ordering and block creation processes. The remaining nodes act as followers, replicating the decisions made by the leader.
- Fault Tolerance: The RAFT consensus mechanism provides fault tolerance by allowing the network to continue operating even if some nodes fail. In the event of a leader node failure, a new leader is automatically elected, ensuring continuous operation.
- Lightweight Operation: RAFT is computationally lightweight compared to PoW, which makes it suitable for environments with limited resources, such as fog and cloud computing layers in smart farming. This also helps to reduce the energy consumption associated with running the blockchain, making the system more sustainable for long-term use.

RAFT ensures that every transaction is validated by consensus across the network before being added to the blockchain. This guarantees that all participants agree on the current state of the blockchain, providing a consistent, reliable record of all farming activities.

4-3- Data Security and Privacy

Blockchain's decentralized structure ensures that data stored within the smart farming system is secure and tamper-proof. Each transaction in the blockchain is cryptographically signed, making it impossible to alter or delete data without network-wide consensus. In addition to blockchain's inherent immutability, the following mechanisms further enhance data security and privacy:

- Role-Based Access Control (RBAC): Hyperledger Fabric integrates RBAC to restrict data access based on user roles within the farming system. For instance, a farmer might only have access to crop data, while an agronomist might have additional access to livestock or soil health data. This

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ensures that sensitive information is only available to authorized personnel, reducing the risk of data breaches or unauthorized access.

- Public-Key Cryptography: Every participant in the blockchain network is identified using public-key cryptography generated by ECDSA in Hyperledger Fabric. Each user has a unique public-private key pair, where the public key is used to identify them on the network, and the private key is used to sign transactions. This ensures that all data transfers are secure and that only authorized parties can modify or contribute to the blockchain.
- Data Integrity: Each block in the blockchain contains a cryptographic hash of the previous block, creating a chain of blocks that are cryptographically linked. This ensures that if anyone attempts to modify a previous transaction, it would invalidate the entire blockchain, making tampering evident and virtually impossible.

These security and privacy features make Hyperledger Fabric an ideal choice for integrating IoT in smart farming, ensuring that all data, whether crop monitoring or livestock management, remain secure, transparent and trustworthy.

5. Result and Discussion

5-1- Experimental Setup

The experimental setup was focused on evaluating the performance of chaincode operations within a permissioned blockchain framework relevant to smart farming. The Hyperledger Fabric network was deployed locally using Docker containers and included two peer nodes, one orderer node, and a CouchDB state database. Chaincode was developed in Go and designed to handle basic agricultural operations such

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as createCrop, updateCrop, and queryCrop. The system was tested in a simulated environment using a machine running Ubuntu 20.04, equipped with an Intel Core i7 processor and 16 GB of RAM. Performance metrics including transaction throughput and latency were measured using Hyperledger Caliper, a benchmarking tool for blockchain networks. No physical IoT sensors or agricultural devices were integrated during this phase; rather, the chaincode operations were executed via client applications to simulate transaction flows in a smart farming context.

Table 1. Chaincode functions of the system

Main Function	Operation Type
createCropData	Write
readCropData	Read
createLivestockData	Write
readLivestockData	Read
updateCropSensorData	write
updateLivestockSensorData	write

Table 2. The invoking performance evaluation settings.

Test Number	1 2 3 4
Functions under test	Write operations
work number	5 worker
Transaction number	500 5000 20000 50000
Type of control rate	Fixed-load
transactionLoad(TPS)	writesetting 50 100 150 200

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Table 3. The updating performance evaluation settings.

Test Number	1 2 3 4 5 6
Functions undertest	Write operations
work number	5 worker
Transaction number	5000
Type of control rate	Fixed-load
transactionLoad(TPS)	50 100 150 200 250 300

Table 4. The read operations performance evaluation setting.

Test Number	1 2 3 4
Functions undertest	Read operations
work number	5 workers
Transaction duration	30 seconds
Type of control rate	Fixed-load
Transaction Load(TPS)	1000 2000 3000 4000

5-3- Experimental Result

In the experimental results, we conducted three experiments by varying the transaction load while using rate control with a fixed load. The first experiment focused on the write operation of two functions: invoking crop and livestock data. The second experiment aimed to update crop and livestock sensor data, with the objective of evaluating the system's performance during data update operations. Lastly, the third experiment involved querying livestock and crop information. These experiments provided valuable insights into the system's performance under different transaction loads. All the configurations were tested a number of times and the outcomes were reproduced deterministically almost the same in a Hyperledger Fabric network. As a result, the given throughput and latency figures will be directly measured values of every workload layout. The differences of the performance of the system as depicted in the results are reflected through the differences in write, update and read operations which occur under varied loads of work.

Experiment 1: Write Operations- involved two tests: varying transaction numbers while keeping the transaction load constant at 100 TPS, and varying the transaction load while keeping the transaction number fixed at 5000, is summarized in Table 2. The results shown in Fig. 3 indicates that for the create crop operation, throughput values increased from 86.0 to 156.2 TPS as the number of transactions increased, while latency values remained consistent between 390 and 500 milliseconds. For the create Livestock operation, throughput values ranged from 101.8 to 169.5 TPS with consistent latency values between 390 to 410 milliseconds. In Test 2, shown in Fig. 4, varying the transaction load resulted in throughput values for create Crop ranging from 139.1 to 148.1 TPS, with latency between 240 and 840 milliseconds. Meanwhile, createLivestock throughput ranged from 150.4 to 165.8 TPS, with latency between 210 and 780 milliseconds.

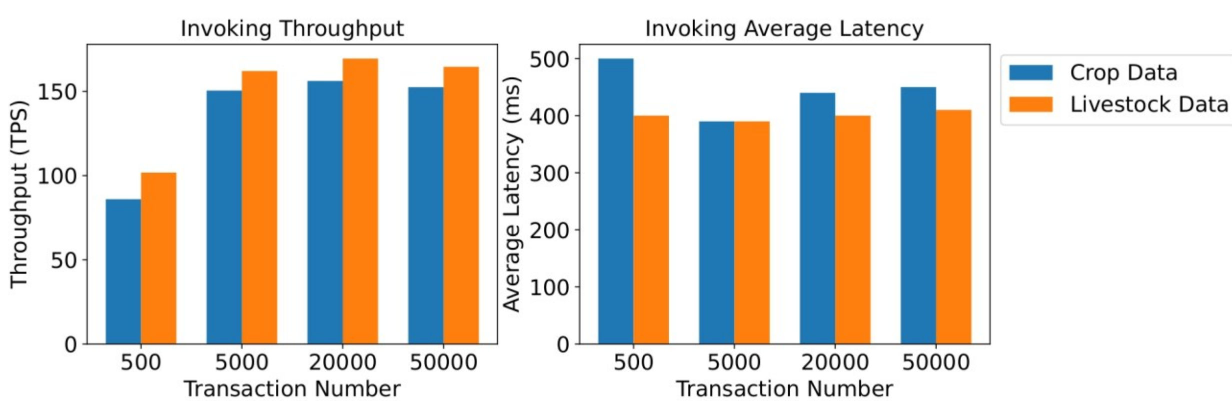

Fig. 3: Throughput and Average Latency for Invoking by Varying Transaction Number

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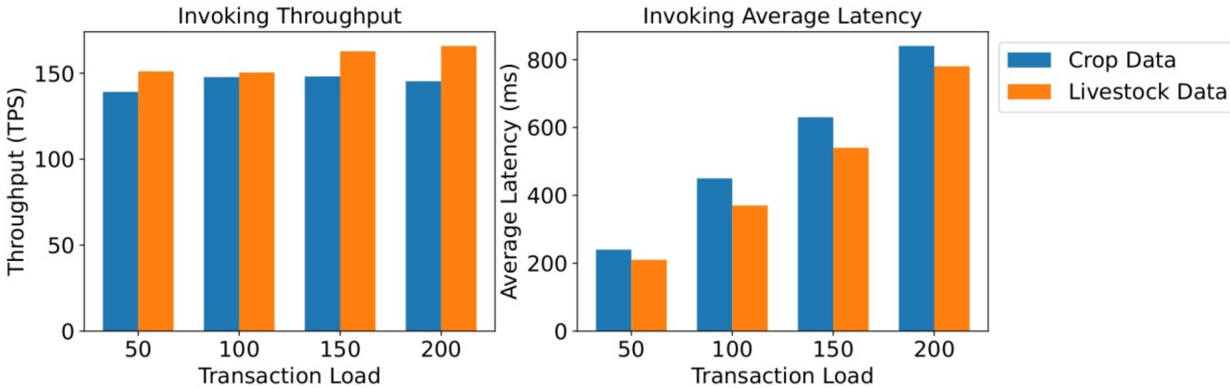

Fig. 4: Throughput and Average Latency for Invoking by Varying Transaction Load

Experiment 2: Update Operations– tested the update crop and livestock sensor operations by varying the transaction load from 50 to 300 TPS as shown in Table 3. The results shown in Fig. 5 indicate that throughput values for the update crop sensor operation increased from 205.2 to 229.8 TPS as the transaction load increased, with latency values ranging from 160 to 840 milliseconds. Similarly, the update livestock sensor operation showed throughput values ranging from 224.6 to 239.7 TPS, with latency between 140 and 750 milliseconds.

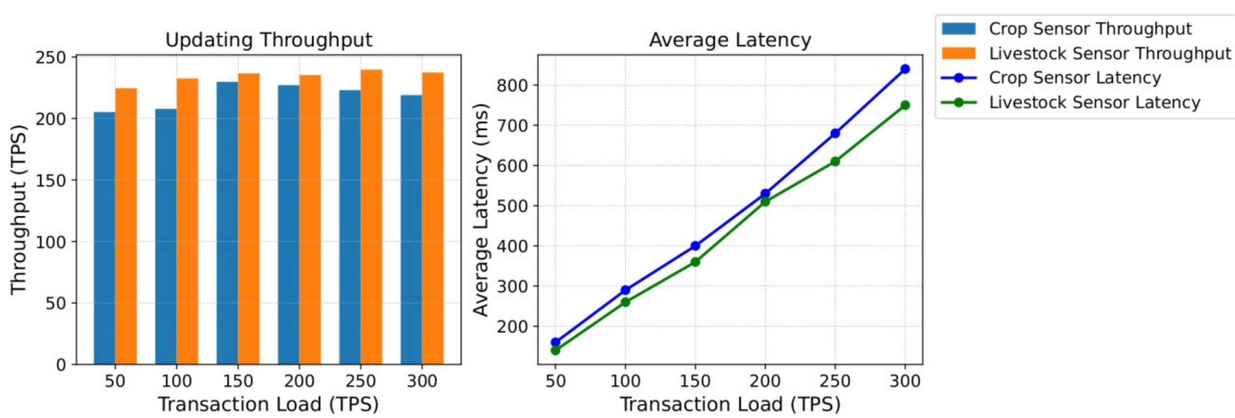

Fig. 5: Throughput and Average Latency for updating sensor data

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Experiment 3: Read Operations – Finally, we tested read-only operations read Crop Data and read Livestock Data to measure querying efficiency. The experimental setup, shown in Table 4, varied transaction loads from 1000 to 4000 TPS. The results shown in Fig. 6 high throughput values for the querying crop operation, ranging from 2479.8 to 2538.5 TPS, and consistently low latency values between 60 to 90 milliseconds. For the querying livestock operation, throughput values ranged from 2395.0 to 2440.1 TPS with latency values between 60 to 80 milliseconds. This indicates efficient processing of a significant number of read-only transactions without significant changes in performance metrics as the transaction load increased.

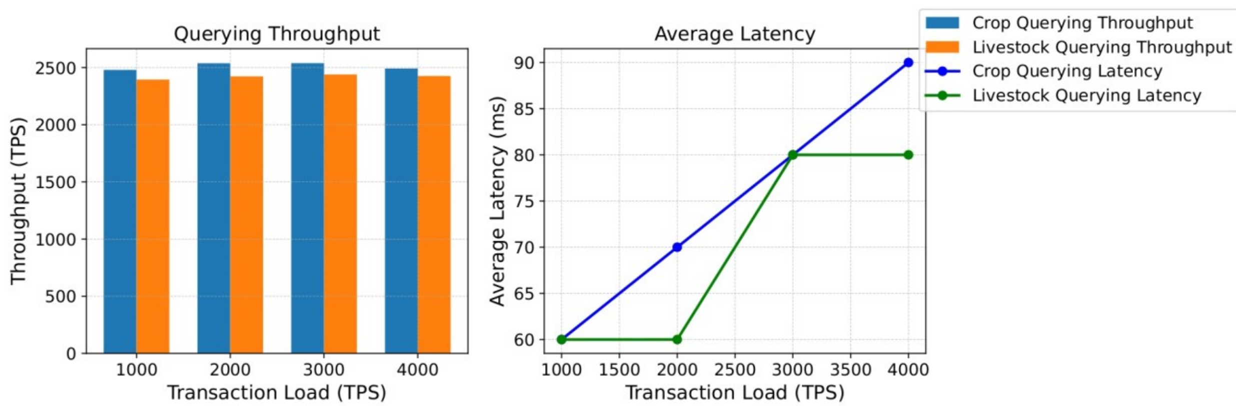

Fig. 6: Throughput and Average Latency for read crop data

6. **Conclusion**

This study presents an efficient integration of blockchain technology with IoT in smart farming, addressing key challenges such as data security, transparency, and data management. By employing Hyperledger Fabric, a permissioned blockchain, the system ensures secure, tamper-proof data handling and decentralized management of farming activities. The proposed four-layer architecture, which includes device nodes, fog computing, cloud computing, and end users, is optimized for real-time data processing, ensuring low latency and high throughput. Through the use of the RAFT consensus algorithm, the system achieves fast and reliable transaction validation, demonstrating fault tolerance and robustness in handling large volumes of data from resource-constrained environments. Additionally, the implementation of Role-Based Access Control (RBAC) ensures that sensitive farming data remains protected, accessible only to authorized users. The blockchain-based IoT framework not only enhances the efficiency of smart farming operations but also performs well in terms of scalability, responsiveness, and security, allowing stakeholders to make timely, informed decisions.

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