FQAChain: A Secure and Transparent Food Supply Chain - Leveraging Blockchain and IoT for Enhanced Traceability and Trust

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**ABSTRACT**

The security, safety, and authenticity of food are major issues in the modern world. Despite being extensive, the global food supply chain faces several difficulties, including phoney labels, the possibility of contamination, and unsustainable practices. Consumer health and environmental sustainability are at risk as a result of these problems. The demand for a safe and open food supply system has increased along with the world population's steady rise.As a creative solution to these problems, "FQAChain" pioneers the integration of blockchain and IoT technology. This method effortlessly combines the transparency and immutability of blockchain technology with real-time monitoring and data collecting using IoT devices. Its key elements are the thorough documentation of product information, the involvement of blockchain in assuring data immutability, and the development of distinctive Non-Fungible Tokens (NFTs) to validate each food item.'FQAChain' empowers customers by providing real-time product information through user-friendly interfaces, ensuring product authenticity while boosting responsibility across the supply chain. It enables customers to make knowledgeable decisions and acts as a driver for improvement in the food business. 'FQAChain' represents a paradigm-shifting step towards a more safe, open, and environmentally conscious food supply chain by making it easier to assess the environmental effect and sustainability of food production and distribution. It goes beyond simple innovation, successfully meeting the urgent demands of our time and providing benefits to producers, consumers, and the environment.

**Keywords**—NFT, Blockchain,Zero Knowledge Proof,Cryptography

# INTRODUCTION

 In the modern world, supply chain integrity and food security are of utmost importance due to the constantly growing global population. Assuring the integrity, safety, and sustainability of our food supply is of utmost importance. This voyage explores the core of the food supply chain, where innovation is required and demand for a safe and open system has risen to unprecedented levelsThe relevance of the project extends beyond only food production and has larger ramifications. These effects range from consumer health and ethical sourcing to environmental preservation. The objective is not only essential, but also everyone's duty in an age where ethical consumption and environmental responsibility have taken centre stage.Traditional methods have long operated in isolation and with inefficiencies throughout the food supply chain. This quest aims to break down these divisions and present a technology-driven, all-encompassing solution. We challenge the norms of an opaque supply chain by merging blockchain, Non-Fungible Tokens (NFTs), zero-knowledge proofs (ZKPs), and cryptography.This project tries to address a variety of issues, such as misleading labelling, contamination hazards, and unsustainable practises. These difficulties jeopardise the safety of our food supply, as well as consumer health and environmental sustainability.The goal is to transform the food supply chain from an outdated, opaque system into a modern wonder that is visible, secure, and environmentally responsible. The objective seeks to overcome the problems that conventional techniques face and create a new benchmark for the sector by incorporating cutting-edge technology and fresh ideas.The main objective is to show how the fusion of blockchain, NFTs, ZKPs, and cryptography can transform the food supply chain into an example of authenticity, security, and transparency. In addition to changing the way food is produced, delivered, and eaten, this study aims to empower consumers, promote ethical sourcing, and reduce the likelihood of fraud and tainted food along the supply chain. The goal is not just an investigation; it is a call to action for a more safe, open, and environmentally conscious food supply chain that will benefit both consumers and farmers as well as the environment.

## **Blockchain**

 Blockchain is a decentralised digital ledger that securely and interconnectively records data and transactions. To create a tamper-proof linkage, each block in the chain consists of transaction data, a cryptographic hash of the data, and the hash of the preceding block. Blockchains fall into three categories: federated (partially private), public (accessible to anonymous users), and private (limited to a particular organisation).A blockchain is made up of several essential parts, such as a database that stores immutable transaction details, a network of linked blocks, cryptographic hashes for data security, miners who solve challenging cryptographic puzzles to validate transactions, and consensus techniques like proof of work and proof of stake to guarantee the blockchain's availability, integrity, and privacy. In order to reach consensus, proof of stake picks validators according to their stake in the blockchain, whereas proof of work requires miners to demonstrate their efforts to add blocks to the chain.

With the conditions of the contract explicitly encoded into code, smart contracts—self-executing agreements—have grown in favour inside blockchain networks. Utilised in industries like real estate, insurance, and law, they automate complicated procedures, doing away with middlemen. Beyond that, voting systems can benefit from blockchain's ability to improve election security and integrity through fraud prevention and precise vote counting.

Furthermore, blockchain's immutability makes it incredibly important for copyright and intellectual property protection, guaranteeing that authors and artists get the credit and money they deserve. Blockchain is also making progress in ensuring the provenance and authenticity of luxury items, hence reducing counterfeits, thanks to its tamper-proof data storage. The distributed ledger technology is going to change data management and financial systems in the digital era by guaranteeing security and trust in a variety of sectors.

## **NFT**

 NFTs, or Non-Fungible Tokens, represent a digital form of ownership, akin to owning a unique token that grants access and ownership rights to a specific digital item, including any associated copyrights. These tokens are securely stored on a blockchain alongside a unique code and metadata, offering a brief description of the NFT.

Digital assets, such as music, digital art, or movies, have historically been susceptible to easy replication. However, minting these assets as NFTs ensures that the owner enjoys full and exclusive access to the item. This innovation significantly reduces the risk of counterfeits and fraud, benefiting both collectors and creators, who can now receive their rightful royalties without intermediaries.

NFTs find widespread application in blockchain-based video games, enabling players to create, own, trade, and collect unique in-game assets in a digital, non-physical format. Traditional online games lack this level of ownership, granting game studios complete control over licensing, ownership, and distribution.

The core purpose of NFTs is to establish ownership of digital assets in a way previously unattainable. In the past, proof of ownership relied on physical records, receipts, or ledgers. NFTs signify the onset of a Digital Ownership Revolution, potentially reshaping how we assert digital ownership. Conventional digital ownership systems tend to be centralized, vulnerable to hacking, manipulation, and misuse. In contrast, NFTs are inherently resistant to such attacks due to their decentralized nature, free from central control. Furthermore, NFTs leverage blockchain technology, deriving their security and reliability from its decentralized architecture. Blockchains serve as distributed networks where individual nodes maintain a ledger of all ongoing transactions. This inherent transparency and security make blockchains a dependable solution not only for tech-savvy individuals but also for the broader public.

 

**Figure 1: NFTs**

# LITERATURE SURVEY

Many technologies have been implemented to deal with various challenges in food supply management. A sample of 10 papers has been taken based on food supply management methods provided by them. This literature survey deals with the enhancement of food supply management primarily using Blockchain

In his paper "Blockchain-based Traceability in Agri-Food Supply Chain Management: A Practical Implementation," the author discusses the expanding demand for trustworthy and open traceability systems in Agri-Food supply chains, particularly in light of the growing IoT usage. The article proposes AgriBlockIoT, a decentralised blockchain-based system combined with Internet of Things (IoT) devices to simplify data tracking and recording along the supply chain. By installing AgriBlockIoT in a "from-farm-to-fork" use case on the Ethereum and Hyperledger Sawtooth blockchains and comparing their performance metrics, it assesses AgriBlockIoT.The study discusses the adaptation of the proposed layered architecture to multiple blockchain platforms while highlighting the potential of blockchain in boosting transparency and trust in Agri-Food supply chains. It attempts to satisfy needs particular to the agri-food sector, giving customers access to comprehensive product histories. The study offers initial findings and draws the conclusion that selecting a blockchain implementation depends on a number of parameters. It also advises further research that includes evaluating the solution on IoT devices in the agri-food supply chain[1]..

The paper "Food Traceability and Prevention of Location Fraud using Blockchain" discusses the critical need for food traceability and fraud prevention across the food supply chain. It emphasises how blockchain technology has the potential to promote authenticity, stop counterfeiting, and improve traceability. The suggested solution, built on the Nxt blockchain platform, makes use of physically protected computers at supply chain points, QR codes for data on goods and transactions, and Android applications for updating and gaining access to blockchain data.The paper illustrates the viability of a blockchain-based food traceability system while underlining the relevance of decentralisation and safe physical access for data integrity by outlining the system's design requirements, deployment, and evaluation against fraudulent activities. The success of the system as a proof-of-concept is acknowledged in the paper's conclusion, which also emphasises the need for further commercialization, scalability, and benchmarking[2].

In this research paper, the author explores the crucial area of using blockchain technology to ensure the integrity of Indonesian Halal food, a subject at the intersection of food safety, health, quality, and religious compliance. The paper offers a country-specific model tailored to Indonesia, given the scant prior research on the role of blockchain in the context of Halal food. It addresses urgent problems like the absence of a unified information system, the pressing need for traceability and transparent access to Halal certification data, and doubts about the effectiveness of governmental oversight in certifying Halal food for the Muslim population. The suggested framework includes a range of stakeholders, such as the Indonesian Halal authority and Halal supervisors, and so presents a thorough plan for maintaining the quality of Halal food along the whole supply chain. The article uses blockchain technology to bring transparency and real-time traceability to the Halal food sector, eventually fostering confidence amongst all parties involved[3].

The use of blockchain technology to handle cold supply networks for perishable food goods is examined in this paper. It presents the idea of an immutable ledger that is transferred from the farm to the customer, protecting vital information about food—such as temperature, production specifics, and dates—from any tampering. The main goals of this technology integration are to reduce food losses, minimise manufacturer financial losses, minimise foodborne diseases, and eventually increase customer confidence. The article emphasises how crucial it is to maintain similar conditions along the whole supply chain, especially for perishable commodities that are particularly sensitive to temperature changes.Traditional supply chains lack transparency, which frequently leads to food waste and safety issues. These issues are addressed by the advent of blockchain technology, which offers a safe and transparent system that improves the effectiveness and security of cold supply chain management. The method put forward in this research shows great potential for reducing food losses, raising safety standards, and boosting customer trust. The introduction of autonomous cars to further improve the supply chain process is one possible development for the future[4].

In this paper, the author investigates how blockchain technology might be applied to the food supply chain management industry in order to address urgent concerns about food safety and traceability. In the study, a working prototype of a food network system built on blockchain technology is shown. Its goal is to securely track and identify the origins of food supply to guarantee reliable traceability and the safety of food items. This system makes use of blockchain technology to safely store and trace food transaction data, providing a clear picture of how those goods moved through the supply chain.The model presents a comprehensive strategy for preserving the integrity of the food supply by involving several layers of stakeholders, such as farmers, suppliers, retailers, and regulators. The study also emphasises how the blockchain may help the food industry increase customer trust and transparency while resolving possible flaws and difficulties in supply chain management. Overall, this study makes a significant addition to the field of blockchain applications in food management and shows great promise for enhancing security in food supply chains[5].

This paper examines the theoretical use of blockchain technology to the management of the agricultural food supply chain, suggesting hopeful answers to pressing problems like food safety, traceability, and transparency. The study emphasises the critical nature of food safety and describes how the decentralised, transparent ledger of blockchain can safely store the complete history of food goods, from manufacturing to consumption. The blockchain's security and immutability, as well as the function of smart contracts in automating procedures and getting rid of middlemen, are highlighted. The management of digital assets in the agricultural supply chain has been demonstrated to benefit from tokenization, especially through the use of ERC-20 and ERC-721 tokens. To improve real-time traceability, integration with IoT devices is recommended. All stakeholders are encouraged to participate, building a network of efficiency and trust. The study also highlights how blockchain may improve the supply chain, guarantee regulatory compliance, and offer future potential while admitting the real-world implementation issues that need to be solved[6].

The author focuses on a large-scale initiative that aims to revolutionise the agricultural supply chain with a focus on food goods by tackling major concerns including transparency, issues with trust, and farmer exploitation. The suggested remedy entails the strategic application of blockchain technology, particularly making use of the Ethereum platform. Immutable ledgers are created using Ethereum's fundamental properties, such as transparency, immutability, and smart contract capability, in order to fully track the supply chain journey from the beginning stages of planting to the final delivery to customers. In order to promote fairness and transparency in the supply chain, smart contracts are essential.The inherent decentralisation of Ethereum promotes confidence among the many parties involved and successfully reduces the dangers brought on by fraudulent actions. By supplying Ethereum addresses to authenticate the many nodes taking part in the supply chain, the Central Authority plays a crucial role in this project. To ensure transaction correctness and avoid potential timestamp manipulation, the critical elements of tracing processes, reputation management, and timestamp reliance are given priority. In conclusion, the author's initiative leverages the potential of blockchain technology, with an emphasis on Ethereum, to usher in a new era of openness, justice, and traceability inside the agricultural supply chain while boosting system dependability and integrity[7].

This paper discusses how blockchain technology is becoming more and more relevant in the food business as a way to combat problems like fraud and improve transparency and traceability. By adding perceived trust as a crucial aspect, it expands the Unified Theory of Acceptance and Use of Technology 2 (UTAUT2) model and focuses on understanding customers' views and intents towards blockchain in this context. According to variables including performance expectations, effort expectations, social influence, enabling conditions, hedonic motivation, habit, and price value, the study examines a number of theories on customer purchase intentions.The major factors driving customer adoption are perceived trust and information transparency, with technology having an additional role. Using structural equation modelling, data from 264 respondents were analysed, highlighting the significance of trust as a factor influencing purchase intention. The practical ramifications highlight the significance of using blockchain technology to increase customer trust and provide value. In summary, this study makes a theoretical contribution by recognising the importance of technographics in understanding consumer behaviour and including perceived trust into the UTAUT2 model. It also acknowledges the need for more regional studies to confirm the findings[8].

This author emphasises the potential for blockchain technology to improve transparency, security, and efficiency within the dairy supply chain in his discussion of the installation of a blockchain-based supply chain management system dedicated to dairy products. The article discusses supply chain management issues and proposes blockchain as a game-changing way to reduce mistakes, fraud, and inefficiency. The suggested system attempts to create a safe, effective, and transparent supply chain network by using technologies like Hyperledger Fabric, Hyperledger Composer, Docker, Loopback, and IPFS.While blockchain technology guarantees data immutability and transparency, the implementation of smart contracts enforces compliance with quality requirements. The study highlights the benefits of this strategy, which include removing expired items and reducing human paperwork and income distribution. It also emphasises the promising potential of blockchain in transforming the management of the supply chain for dairy products[9].

This paper explores how supply chain efficiency and dependability may be improved by using blockchain technology to alter numerous industries. It describes blockchain as an unchangeable, secure distributed ledger system that doesn't require centralised authority, making it perfect for intricate supply networks. Manufacturing aircraft components and transporting very valuable live seafood are two particular application cases that being investigated. The first illustrates how blockchain might streamline certification procedures for aircraft parts, and the second emphasises the advantages of real-time data for tracking the health of seafood that is being transported. The main takeaway is that companies with complex supply chains and demanding quality control requirements may tremendously benefit from blockchain technology's tamper-proof, transparent, and secure properties, ultimately benefiting the interests of both businesses and consumers[10].

#  METHODOLOGY

## **Existing System**

The AgriBlockIoT system architecture is a ground-breaking strategy for tackling the difficulties the Agriculture and Food (Agri-Food) supply chain faces. There is a glaring lack of transparency, traceability, and auditability in the Agri-Food business given the existing state of logistics information systems. By creating a layered architecture that leverages the power of blockchain technology and the Internet of Things (IoT), AgriBlockIoT aims to alter this. Blockchain technology is ideally suited for creating trustless systems inside the supply chain since it offers decentralisation, immutability, and transparency at its heart.

Three essential parts make up this architecture. The user-friendly interface of the API makes it easier to communicate with the system and allows for integration with other software programmes. The Controller ensures smooth data flow and function execution by acting as a critical middleman between the high-level API and the blockchain layer. The system's foundation is the Blockchain layer, which is powered by either Ethereum or Hyperledger Sawtooth and contains the smart contracts and business logic needed to manage transactions. The system's resilience and security are further improved by the incorporation of IoT sensors and devices together with contemporary edge devices like gateways and mini-PCs.

For the agri-food supply chain, AgriBlockIoT aims to provide a decentralised and safe traceability solution. The solution efficiently combines blockchain technology and IoT devices to assure data integrity and immutability, promoting better supply chain transparency and trust. Additionally, because of its adaptive layered design, which enables easy interaction with current software systems, it can meet the Agri-Food industry's rising demand for transparency and traceability. AgriBlockIoT provides enormous promise for solving the particular difficulties faced in this business as the technology develops.

 AgriBlockIoT addresses the urgent demand for dependability and transparency in the agri-food supply chain, a field where upholding integrity and trust is crucial. A perfect foundation for attaining transparency, traceability, and auditability is provided by the system's layered design as well as the inherent qualities of blockchain and IoT technologies. AgriBlockIoT enables that customers have access to thorough product histories by providing a full perspective of the supply chain, hence boosting food quality and safety. The system's flexibility to various blockchain platforms and potential for seamless IoT device integration serve to further emphasise its advantages. AgriBlockIoT is a trailblazing solution ready to increase transparency and confidence in the sector, helping all stakeholders as the agri-food industry continues to develop and embrace digital innovation.

However, AgriBlockIoT does have its disadvantages, which must be acknowledged to gain a comprehensive understanding of its limitations:

**Scalability Challenges**:Although the article briefly notes the selection of Hyperledger Sawtooth as having superior performance over Ethereum, it neglects to address the core scalability issue. Blockchains frequently experience scaling problems, especially open-source blockchains like Ethereum. The handling of an increasing number of transactions on these platforms as the Agri-Food supply chain grows might result in slower transaction processing times and greater costs, which are crucial concerns that are not fully addressed in the article.

**User Onboarding Complexity:** The paper does not give stakeholders a thorough review of user onboarding procedures. Many players in the real-world agri-food sector might not be tech-savvy. Because of the public-key cryptography and blockchain technology used by AgriBlockIoT, farmers, distributors, or customers may have a long learning curve. To make sure that adoption goes well, a more elaborate plan for user assistance and training is required.

**Operational Disruptions:**The system takes IoT device abnormalities into account, but it does not go into great detail about operational disturbances that can impair data flow. In reality, sensor malfunctions, power outages, or network problems might obstruct the blockchain's constant data logging. A thorough plan for dealing with such interruptions is missing from the document, which is essential for preserving data integrity and traceability.

**Economic Considerations**: The economic advantages of private networks are briefly mentioned in AgriBlockIoT, however the system's long-term costs and viability are not covered. The players' motivations and economic viability are important but understudied issues. To encourage continuous engagement, a thorough examination of the possible financial costs or gains for different stakeholders is needed.

**Regulatory and Compliance Issues**: The regulatory and compliance considerations unique to agri-food supply chains are not fully covered by the paper. Regulations governing food safety, traceability, and data privacy differ by area. It is crucial to go into further detail about how AgriBlockIoT can adjust to different legal frameworks.

## **Proposed System**

The proposed system consists of the seven modules: namely Product Data Recording and Verification Module,IoT Data Integration and Verification Module,Creation and Management of NFTs Module,Blockchain and Smart Contract Module,Zero-Knowledge Proof and Data Privacy Module,Cryptocurrency and Token Rewards Module,User-Friendly Front-End Module

**1. Product Data Recording and Verification Module:**

This module is designed to meticulously record and validate real-time data associated with food products throughout the supply chain. The key steps involved are as follows:

 **Data Collection:**The process of gathering data starts at the source, which might be one of the food processing facilities, farms, or industrial facilities. A variety of Internet of Things (IoT) devices are used to collect this data. As the food goods move through the supply chain, a variety of sensors on these devices continually gather a wealth of data about them. Critical information like the product's origin, the particular techniques used in its manufacture, and the circumstances of its transportation are all included in the real-time data collected.

 **Data Verification:** After the data is gathered from the Internet of Things devices, it goes through a thorough verification procedure in real time. An essential first step in guaranteeing that the data is valid and unchanged along the supply chain is verification. Sophisticated validation methods are used to examine the data and protect against any possible manipulation or errors. These validation procedures provide a crucial extra degree of protection to ensure that the information gathered is correct and trustworthy.

By employing this module, the FQAChain ecosystem can maintain a continuous record of data associated with food products, which serves as a foundation for transparency and traceability. This secure and verifiable data is crucial for not only enhancing consumer trust but also for streamlining various supply chain operations.

**2 .IoT Data Integration and Verification Module**

This module concentrates on the integration of data from IoT devices while ensuring its validity. The steps involved are as follows:

**Data collection**: The procedure begins with Internet of Things (IoT) devices that are positioned strategically at different stages of the food supply chain, from farms and production facilities to regions used for transit and storage. Numerous sensors on these Internet of Things devices are gathering data in real time. These sensors track location, temperature, humidity, and other important environmental factors while gathering insightful data about the food products' travels.

**Data Transmission:** As soon as the Internet of Things devices have gathered data, it is securely sent in real time to the FQAChain ecosystem. Communication methods that are encrypted are used for this transfer. Data is sent into FQAChain as fresh batches of food goods are carried, guaranteeing the data's security and integrity throughout the journey. Ensuring the security and integrity of the data during its path is crucial.

**Data Validation**: In real-time, sophisticated validation processes are applied to the incoming data. This validation procedure is essential to confirming the data's legitimacy. These methods of validation are intended to protect against any possible manipulation or change, guaranteeing that the information gathered is accurate and unaltered. Only accurate and unaffected data is accepted into the system thanks to this real-time checking.

**IoT Device Management**: This module contains real-time management features to guarantee the secure and correct operation of IoT devices. Firmware upgrades and remote diagnostics are two possible examples of these features. The module ensures that IoT devices stay functional throughout the supply chain by offering safe and continuous device management.

This module's real-time data gathering, integration, and validation capabilities are the main thing to remember. It plays a crucial role in maintaining the accuracy and consistency of data as food products move from their point of origin to the customer, enhancing the ecosystem of FQAChain's general transparency and confidence.

**3.Creation and Management of NFTs Module**

This module primarily deals with the generation and management of NFTs (Non-Fungible Tokens) for food products, essential for ensuring authenticity and traceability. The steps involved are as follows:

 **NFT Generation:** The process starts as soon as food products are added to the FQAChain network. Currently, each product has a real-time NFT produced for it. For the product, this NFT acts as a distinct digital certificate. It serves as a virtual copy of the real thing, forging an unbreakable connection between the real and virtual versions of the product. The digital identity of the product is protected, distinct, and unchangeable thanks to this link.

**Metadata Inclusion:** Every NFT is enhanced in real-time with a comprehensive collection of product-specific metadata. The product's important facts, including its origin, ingredients, certifications, and any other pertinent information, are included in this metadata. Customers and other stakeholders who want to evaluate the product's originality, quality, and standard compliance must have access to this information. Incorporating this metadata improves trust and transparency across the supply chain.

**Blockchain Integration:** These NFTs are safely kept on the blockchain in real-time. Through this integration, the digital certificate (NFT) and the tangible product are linked in an unchanging and impenetrable manner. This indicates that the connection between the digital certificate and the product is safe and unchangeable after the NFT is placed on the blockchain. A crucial component of guaranteeing data integrity and product validity is this strong link.

**Ownership and Transfer**: Throughout the food supply chain, NFTs are essential for determining and overseeing who owns what. These NFTs are automatically sent in real-time whenever a product is exchanged. Smart contracts, which are self-executing contracts that guarantee safe and transparent ownership transfers, are used to carry out the procedure. At every stage of the supply chain, this rapid and safe transfer of ownership improves responsibility and confidence.

To put it briefly, this module focuses on the creation and management of NFTs in order to build food products' digital identities. These NFTs provide smooth and safe ownership transfers, safeguard the digital connection between the product and its certificate, and encapsulate product-specific metadata. The FQAChain ecosystem depends on this module to maintain authenticity, transparency, and trust.

**4.Blockchain and Smart Contract Module**

 This module involves the use of blockchain technology and smart contracts to ensure transparency and secure transactions within the FQAChain ecosystem. The key steps in this module are as follows:

**Public and Private Blockchains:** In order to optimise various system components, FQAChain uses a hybrid blockchain framework that integrates both public and private blockchains.

**Public Blockchains**: High-level transaction data, such as the formation of NFTs and ownership transfers, are recorded in real-time on public blockchains. This public ledger gives a clear, unchangeable record of these high-level actions and guarantees complete openness. Transparency is essential because it makes it possible for stakeholders to confirm and track the origin, transfer, and ownership of NFTs and food items, which strengthens ecosystem confidence.

**Private Blockchains:** Smart contracts and transaction processing are handled by these private blockchains. Private blockchains provide a scalable and effective platform for carrying out different processes in real-time. Here, self-executing contracts, or smart contracts, are crucial because they guarantee the speed, accuracy, and security of transactions like buying products.

**Smart Contract Execution:** During customer transactions, smart contracts are activated. The transaction involving the purchase of food products is carried out on the private blockchain. These smart contracts control the safe transfer of ownership, instantly carry out financial transactions, and confirm the legitimacy of the goods.

In short, everything revolves on using the potential of smart contracts and blockchain technology inside the FQAChain network. The integration of both public and private blockchains guarantees openness in high-level operations, while smart contracts enable safe and effective transaction handling. The foundation of the system's systems for accountability, security, and fostering trust is this module.

**5.Zero-Knowledge Proof and Data Privacy Module**

This module is crucial for safeguarding sensitive data and maintaining data privacy within the FQAChain ecosystem. The steps and significance of this module are as follows:

**Sensitive Data Request:** This module starts when a customer or other stakeholder wishes to confirm certain details about a food product, including its organic certification. The FQAChain system is used to start this request in real time.

**Zero-Knowledge Proof Verification:** The FQAChain system uses cutting-edge encryption methods, such as Zero-Knowledge Proofs (ZKPs), in real-time. These cryptographic instruments are essential for protecting sensitive information. ZKPs give stakeholders the ability to confirm the veracity and correctness of data without disclosing the actual data. Put simply, this implies that a stakeholder can provide evidence of a fact (such as the organic status of a product) without providing the supporting data. This method greatly improves privacy and data security.

**Data privacy:** Real-time Zero-Knowledge Proofs make sure that only those with permission may access certain data. This creative strategy ensures that private information stays private for all parties concerned. Essentially, it provides a means of information verification while safeguarding private information from unauthorised parties.

**Secure Verification Result:** The stakeholder receives a secure verification result upon the completion of the verification procedure. For instance, a customer may instantly verify if a product is organic without disclosing the underlying certification information. The participants' confidence is increased by this extra security and privacy layer.

**Privacy Across the Ecosystem:** The Zero-Knowledge Proof and Data Privacy Module, which is significant, gives real-time data privacy to every member of the FQAChain ecosystem. This implies that sensitive data may be kept private while information can be verified by farmers, wholesalers, and other stakeholders in addition to customers. Throughout the whole supply chain, confidence is strengthened by an all-encompassing approach to data privacy.

In conclusion, this module makes sure that confidential and sensitive data stays that way even when stakeholders need to confirm specific details. The cornerstone of this module is Zero-Knowledge Proofs, which enable safe data verification while instantly protecting sensitive information. Establishing trust and openness within the FQAChain ecosystem is largely dependent on this method.

**6.Cryptocurrency and Token Rewards Module**

This module deals with cryptocurrency transactions and token-based rewards within the FQAChain ecosystem. The steps and significance of this module are as follows:

**Cryptocurrency Transactions**  : This module starts when users in the FQAChain ecosystem choose to conduct transactions using cryptocurrency. FQA Coins, the ecosystem's own digital currency, are used in these transactions. FQA Coins may be used for a number of things, including as buying food items, transferring product ownership, and taking part in reward schemes.

**Blockchain Recording:** Every cryptocurrency transaction is instantly recorded on the blockchain to guarantee traceability and transparency. Every transaction is safely stored on the blockchain ledger, which produces an impenetrable record of all financial transactions inside the ecosystem.

**Token-Based Rewards:** The module keeps track of and evaluates user contributions to the FQAChain network on a continual basis. This entails keeping track of actions like encouraging openness, providing feedback, or interacting with other ecosystem components. Real-time FQA Coin rewards are given to participants for significant efforts. Users are incentivized to participate actively and make meaningful contributions to the ecosystem through these benefits.

**User Access:** Users may quickly access their FQA Coins and see a real-time history of their transactions. This data, which provides complete transparency about their cryptocurrency holdings and transaction activity, is accessible within the FQAChain ecosystem.

**Community Involvement:** Consumers who instantly get FQA Coins can use them to buy more products or give them to other users in the ecosystem. This feature encourages participation in the community by letting users utilise their rewards on worthwhile exchanges and interactions. It adds to a thriving, dynamic ecology.

To put it briefly, this module uses token-based incentives and cryptocurrencies to make the FQAChain ecosystem more lively and interesting. It invites users to actively participate, make constructive contributions, and be a part of a vibrant community that is focused on transparency and high-quality food items in addition to making transactions easier.

**7.User-Friendly Front-End Module**

 This module focuses on the user interface and user experience, making it easy for stakeholders to interact with the FQAChain system. The steps and significance of this module are as follows:

**Simplified Onboarding:** The first step in this module is to make it easier for stakeholders, such as farmers, customers, and other participants, to get started. The goal is to make it simple and intuitive for anyone to sign up and take part in the FQAChain ecosystem. QR code technologies and smartphone applications are used to do this. To register and control their devices, users only need to install the smartphone app and complete a few simple steps. Because the onboarding procedure is so simple, anyone who isn't familiar with blockchain technology may join the ecosystem with ease.

**Product Information Access:** This module's main goal is to provide consumers' easy access to comprehensive product information. Food goods labelled with QR codes may be seen at supermarkets and grocery stores. Customers may quickly and simply scan these QR codes in real time with their cellphones. They may instantly access a plethora of information about the goods they are interested in with this easy activity. This data consists of the product's country of origin, manufacturing processes, certifications, and even reviews left by past buyers. Customers are empowered to make educated selections when they buy because to the user-friendly interface's degree of openness and data accessibility.This aligns with the core values of the FQAChain system, where transparency and trust are paramount.

In conclusion, this module concentrates on developing a smooth and intuitive interface for all parties involved, particularly customers. The module facilitates user engagement with the FQAChain ecosystem by streamlining the onboarding process and improving access to product information. This, in turn, encourages transparency and well-informed decision-making in the food supply chain.

### **Table 1:Comprehensive Sensor Deployment Overview for Precision Agriculture.**

| **Sl No** | **Sensor Name** | **Sensor location** | **Information Obtained** | **Use in FQAChain** |
| --- | --- | --- | --- | --- |
| **1** | Soil Moisture Sensor | In the soil | Soil moisture levels (percentage) | Helps optimize irrigation by providing real-time data on soil moisture, reducing water wastage and ensuring crops receive the right amount of water. |
| 2 | Leaf Temperature Sensor | On or near crops | Leaf temperature (in degrees Celsius) | Monitors plant stress due to extreme temperatures, allowing for timely interventions to protect crops from heat or cold damage. |
| 3 | GPS Sensors | On farm machinery | Geospatial coordinates (latitude and longitude) | Tracks the movement of farm machinery and provides precise location data for monitoring field operations and managing equipment efficiently. |
| 4 | Drone-mounted Cameras | Attached to drones | Aerial images and multispectral data | Collects data on crop health, disease detection, and growth status, enabling early identification of problem areas and informed decision-making. |
| 5 | Weather Station | Within or near fields | Weather parameters (temperature, humidity, wind speed, precipitation) | Offers real-time weather data to predict weather-related risks, optimize planting and harvesting schedules, and manage resources efficiently. |
| 6 | IoT Soil Sensor | Scattered across the field | Various soil data (moisture, temperature, pH, nutrient levels) | Provides detailed soil health information to fine-tune fertilizer application and optimize crop-specific soil conditions. |
| 7 | Pesticide Application Sensor | Attached to pesticide equipment | Pesticide application rate (liters per hectare) | Monitors the precise amount of pesticide applied to crops, ensuring accurate and efficient pest control while minimizing excess use. |
| 8 | Fertilizer Application Sensor | Attached to fertilizer equipment | Fertilizer application rate (kilograms per hectare) | Tracks the quantity of fertilizer distributed in real-time, enabling precise fertilization to enhance crop growth while minimizing waste. |



**Figure 2: Flow Diagram**

# ALGORITHMS

1. **Consensus Algorithms:** Consensus methods, like Proof of Work (PoW) are complex cryptographic protocols that force miners to do computationally demanding tasks in order to secure the blockchain network. PoW is reliant on miners competing to solve challenging mathematical puzzles and using their computing resources. By using a more complex economic model, Proof of Stake (PoS) allows users to validate transactions depending on the quantity of tokens they "stake" as collateral. The decentralisation and network security are guaranteed by this complex trade-off between resource consumption and financial incentives.
2. **Cryptography Algorithms:** Sophisticated encryption protocols, such as AES, use extensive substitution-permutation networks and sophisticated symmetric-key encryption algorithms to safeguard the secrecy of data. Similar to this, RSA and Elliptic Curve Cryptography (ECC) protect communications by utilising complex mathematical concepts like prime factorization and elliptic curve equations. The strong security of encrypted data is established by these algorithms through the use of prime number theory and complex mathematical features.
3. **Zero-Knowledge Proof (ZKP) Algorithms**: With the use of sophisticated mathematical concepts like elliptic curve pairings and recursive composition, the advanced cryptographic idea of zk-SNARKs enables one side to demonstrate knowledge of particular information without disclosing that information. While confirming the authenticity of the data, this intricate interplay of cryptographic primitives guarantees a high degree of anonymity. Because zk-SNARKs are based on complex mathematical and cryptographic principles, they offer a sophisticated data privacy solution.
4. **Hashing Algorithms**: To produce fixed-length unique representations of input data, hash functions—like SHA-256—use complex bit-level operations, permutations, and bitwise logic. Through rigorous cryptographic procedures, these algorithms precisely map data to a consistent-sized hash while guaranteeing a low chance of collisions, protecting data integrity and authenticity.
5. **Machine Learning Algorithms**: Neural networks, which use sophisticated weighted connections and activation functions to mimic the neural architecture of the human brain, are examples of complicated algorithms used in machine learning. While clustering algorithms, like k-means, use sophisticated mathematical ideas like Euclidean distance to group data points, decision trees use complicated recursive splitting of data based on complex decision criteria. The identification of complicated linkages, outliers, and detailed patterns in supply chain data is made possible by these elaborate procedures.
6. **Smart Contracts Development**: Creating smart contracts requires using sophisticated programming languages like Solidity, which include sophisticated data structures, functions, and state variables. These contracts guarantee the intricate implementation of intricate agreements within the ecosystem by carrying out sophisticated and automated operations based on sophisticated conditional logic.
7. **Token Standards**: To specify token behaviour inside the blockchain network, complicated data structures like dynamic arrays and complex interfaces are used in token standards like ERC-721 for Non-Fungible Tokens (NFTs) and ERC-20 for Fungible Tokens. These sophisticated standards enable complex transactions and ownership management by defining the complex interactions and regulations that tokens must follow inside the ecosystem.
8. **Data Validation Algorithms:** To generate and validate complicated mathematical representations of data, data validation uses sophisticated cryptographic techniques such as digital signatures. Even in the face of sophisticated attempts at data manipulation, these sophisticated techniques are essential to maintaining the detailed correctness and integrity of complicated data.
9. **Data Integration Algorithms:** These algorithms combine data from several complicated sources into a coherent and complex dataset by means of complex operations such as complex data mapping, complex transformations, and complex purification procedures. The detailed precision and consistency of the data across the ecosystem are guaranteed by these elaborate procedures.
10. **Geospatial Algorithms**: To enable complicated real-time monitoring and complex mapping of geographic data, geospatial algorithms use sophisticated techniques such as R-tree indexing, which is a complex data structure for spatial indexing. Through extensive geographic computations, these elaborate algorithms govern the spatial distribution of items within the supply chain.
11. **Pattern Recognition Algorithms**: Time series analysis and support vector machines (SVM) are two examples of complicated mathematical models and statistical techniques used in pattern recognition algorithms. These sophisticated methods enable complicated data-driven decision-making by facilitating the complex discovery of complex trends, complex anomalies, and recurrent complex patterns in complex supply chain data.
12. **Transaction Verification Algorithms:** To guarantee the intricate legality and security of intricate transactions, transaction verification algorithms make use of sophisticated data structures, such as Merkle Trees, and sophisticated cryptographic approaches. Intricate and transparent transaction processing is ensured by these sophisticated algorithms, which make it easier to validate ownership and authenticate transactions within the ecosystem.
13. **QR Creation Algorithm:**The FQAChain ecosystem relies heavily on QR code production to provide clients with easy access to product information. In order to maintain data integrity, the procedure starts with encoding product facts, such as origin, certifications, and ingredients. Reed-Solomon error correcting techniques are used in this process. The next stage is to divide the encoded data into segments, fit the segments into the grid of the QR code, and use strong error correction methods like Reed-Solomon to guarantee data retrieval even in cases when some of the data are lost or obfuscated. The production of QR codes, which requires complex mathematical computations to determine exact module placement for scan accuracy, is the algorithm's central component. Alignment and timing patterns are positioned by sophisticated algorithms and act as benchmarks for QR code scanners.The QR code's version, format details, size, and error correction levels all add to its complexity. The outcome of intricate bitwise operations, masking patterns enhance readability and visual balance. The harmonic fusion of these intricate elements ultimately produces the final QR code picture, guaranteeing data correctness, redundancy, and longevity. This enhances openness inside the FQAChain ecosystem and provides customers with a powerful tool for gaining access to a multitude of product information.

# WORKING

The FQAChain system is a complete solution made up of seven interrelated parts, each of which is intended to handle a particular issue related to the food supply chain. Transparency, data integrity, and trust within the ecosystem are all dependent on these elements.

In order to strengthen consumer confidence and streamline supply chain operations, it is crucial to carefully record and validate real-time data related to food products, collect data at the source, and continuously monitor vital information like product origin, manufacturing processes, and transportation conditions. All of these actions together create a secure and verifiable data record.

 Encrypted communication techniques are used to securely transfer the collected data in real-time to the FQAChain ecosystem. This assures data integrity and greatly improves data quality and consistency, which raises the system's transparency and builds user confidence.

By creating distinct digital certificates in the form of NFTs, food products may have their validity and traceability established. These NFTs integrate product-specific metadata, such as information about origin, ingredients, certifications, and more, to improve transparency and give customers and other stakeholders important information. By safely keeping these NFTs on the blockchain, you can guarantee an unchangeable link between the digital certificate and the physical thing, enhancing authenticity, facilitating safe ownership transfers, and encapsulating crucial information about the goods.

 

**Figure 2: Representation of Water trap with AI**

Using smart contracts and blockchain technology, public and private blockchains are essential for system component optimisation. High-level transactions, such the generation of NFTs and ownership transfers, are recorded in real-time on public blockchains, guaranteeing total transparency and enhancing ecosystem confidence. Smart contracts and transaction processing are managed by private blockchains, which allow for safe, effective, and quick transaction execution while guaranteeing the authenticity of goods purchases and ownership transfers.

Zero-Knowledge Proofs (ZKPs), one of the sophisticated encryption techniques used in the FQAChain ecosystem, are used in real-time to protect sensitive data and ensure data privacy. ZKPs improve data security and privacy by enabling stakeholders to confirm the correctness of data without revealing the actual data. By limiting access to particular data to only those who are authorised, the system protects personal data from unauthorised parties and promotes confidence and transparency across the supply chain.

Users may transact using FQA Coins, the ecosystem's digital currency, which can be used to buy food, transfer product ownership, and take part in incentive programmes. FQAChain handles cryptocurrency transactions and token-based rewards. An unchangeable record of all financial transactions within the ecosystem is created by using blockchain recording for cryptocurrency transactions, which guarantees traceability and transparency. Furthermore, the system is always keeping an eye on and assessing user contributions to the FQAChain network. Real-time FQA Coin incentives are given to users who actively participate, promote transparency, offer feedback, or engage with other ecosystem components. These users are recognised for their noteworthy efforts. Within the ecosystem, users may examine their transaction history and retrieve their FQA Coins, encouraging community engagement and streamlining transactions.

QR code technology and smartphone applications are used to streamline the onboarding process and make sure that farmers, consumers, and other players may join the ecosystem with ease. To register and maintain their devices, users simply need to install the smartphone app and follow a few easy steps. This makes it easy for people who are not familiar with blockchain technology to join the ecosystem.

Users may also instantly access extensive product information with this technology. Supermarkets and grocery stores carry food items labelled with QR codes. Consumers can instantly obtain a plethora of information about the products they are interested in by scanning these QR codes with their smartphones in real time. This promotes transparency and access to product data, which is in line with the fundamental principles of the FQAChain system and gives customers the power to make informed decisions when making purchases.

# CONCLUSION

The FQAChain has the potential to completely change how we think about, source, and eat food. It is a revolutionary force in the food supply chain. FQAChain solves the industry's enduring problems by combining cutting-edge technology including blockchain, IoT devices, data privacy standards, and cryptocurrency transactions. Product information is kept accurate thanks to strategically positioned sensors that capture data in real-time. End-to-end traceability is made possible by the use of NFTs, which promotes accountability and confidence.

Looking ahead, FQAChain has a tonne of potential. With customers becoming more aware of food safety, quality, and ethical sources, this system offers a way to satisfy their needs. Furthermore, FQAChain's modules provide data that may power machine learning and predictive analytics applications. The system is a vital tool for food producers and regulators since it can detect patterns, quality indicators, and possible problems by utilising this abundance of data. Moreover, the ecosystem of FQAChain may expand beyond food to other categories of goods where authenticity and transparency are critical.

The food sector is undergoing a shift towards more transparency due to the confluence of technology innovation and customer awareness. FQAChain is leading this transformation. It provides a vision for a more knowledgeable, reliable, and sustainable food supply in the future in addition to a solution for the here and now.

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