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Review Article

BLOCKCHAIN TECHNOLOGY: REVOLUTIONIZING AGRICULTURE

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Abstract: Blockchain technology has come out as a life changing force in various sectors, including agriculture, where it provides considerable advancements in transparency, traceability, and efficiency across the supply chain. This review paper explores the uses of blockchain in agriculture, focusing on its applications in smart agriculture, crop insurance, and supply chain management. By examining the advantages of decentralized systems, such as enhanced security, reduced fraud, and real-time payment settlements, the paper highlights key innovations like smart contracts and their role in automating processes and minimizing errors. The review also discusses practical operations through case studies, including AgriDigital's real-time payment solutions, TE-Food's comprehensive traceability system, Ripe.io's detailed food tracking using IoT and AI, AgriLedger's empowerment of small farmers, and Etherisc's automated crop insurance. Despite these benefits, the paper also showcases challenges such as high implementation costs, integration with legacy systems, data security concerns, and limited technological awareness among stakeholders. The paper concludes by emphasizing the need for further research to overcome these obstacles, improve data collection methods, and enhance interoperability and education. Overall, blockchain technology holds significant potential to revolutionize and modify agriculture by improving supply chain management, ensuring food safety, and expanding market access for farmers.

Keywords: *Blockchain technology, Supply chain, Cryptography, Transparency, Internet of Things, Traceability, Radio Frequency Identifier*

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Introduction

Blockchain is a decentralized digital ledger system that utilize cryptography for transaction security and verification. Originally introduced with Bitcoin by Satoshi Nakamoto, blockchain technology (BCT) has evolved to support cryptocurrencies and offers potential uses across diverse sectors. In smart agriculture, BCT can improve supply chain transparency, traceability, and productivity [1]. Blockchain technology derives its name from "block" and "chain," symbolizing a sequence of transaction records, or blocks, connected through cryptographic methods. Each block contains a header that is linked to the previous block. Blockchain operates as a peer-to-peer network which is collectively managed by its participants [2]. It serves as a decentralized system for storing and retrieving information. Each block includes transaction details and a header that stores cryptographic hash values, timestamps, and the root value of the preceding block.

Agriculture is important to the world economy as it provides food and raw materials. As the global population increases, there is an urgent requirement to increase agricultural efficiency and effectiveness. Blockchain technology (BCT) offers a significant solution to face challenges in agriculture, especially in enhancing trust, efficiency, and traceability, which have become more important with recent technological advancements. These aspects are critical for consumers, regulators, and industry stakeholders, and BCT offers a more precise and dependable way to fulfil these needs. The evolution of agriculture today emphasizes the need for novel methods and advancements to foster greater transparency and accountability within the sector. Blockchain technology is emerging as a crucial tool in this regard [3]. Unlike traditional centralized agricultural management systems, blockchain offers a decentralized framework for storing and accessing data that can be shared among numerous untrusted parties. This innovation holds promise in addressing several significant issues present in current agricultural systems.

Modern consumers are increasingly interested in the origins and production methods of their food. However, traditional supply chains, where a single organization manages data, often fail to provide timely access to this information to concerned customers. Blockchain technology is now being explored as a potential solution to longstanding issues in conventional agri-food supply chains by allowing all involved parties to access and verify digitalized information [4]. Blockchain technology holds significant promise for enhancing efficiency, traceability, and transparency within the agricultural supply chain. Potential applications include recording the entire journey of products from planting through harvesting, processing, packaging, and distribution on an immutable and transparent blockchain. This enables customers, merchants, and authorities to verify the authenticity and quality of food products by tracing their supply chain origins.

Additionally, blockchain facilitate with the use of smart contracts, which are automated and enforceable agreements among supply chain participants. These contracts could automate processes such as releasing funds when farmers meet specific conditions, such as delivering a specified quantity of crops. Furthermore, blockchain technology in agriculture can improve logistics and reduce waste by providing real-time access to inventory, demand, and production data. This allows for closer monitoring of supply chain quality and compliance with regulations.

Features of Blockchain Technology

Blockchain possesses several key properties that are highly advantageous for applications in the agriculture sector.

Decentralization: Blockchain operates on a decentralized peer-to-peer network, where groups of systems collectively manage the network. This decentralized nature eliminates the need for a central authority, allowing any participant to store and access data securely via the web using a private key.

This applies not only to cryptocurrencies but also to documents, contracts, and digital assets.

User Anonymity: While blockchain transactions are transparent and traceable through public addresses, user identities remain anonymous. Transactions are recorded permanently on the blockchain with a unique hash value, ensuring transparency without revealing personal details.

Consensus: Blockchain relies on consensus mechanisms to validate transactions before adding them to the chain. This ensures that transactions adhere to predefined rules; any transaction that violates these rules is considered invalid. Blockchain networks can be permissionless or permissioned, allowing public or authorized nodes to participate in consensus.

Immutability: Once recorded, blockchain transactions cannot be altered or deleted. Any errors must be corrected through subsequent transactions, maintaining a transparent and tamper-resistant ledger of all transactions approved by consensus.

Enhanced Security: Each blockchain transaction is securely encrypted using cryptographic techniques like the SHA256 hashing algorithm. This encryption ensures that transactions are secure against unauthorized access and tampering attempts, providing robust security for sensitive agricultural data and financial transactions. These properties make blockchain technology well-suited for various applications within the agriculture sector, enhancing transparency, security, and efficiency in managing supply chains, certifications, and financial transactions.

Blockchain Application in Agriculture

Supply Chain Traceability

In today's globalized and fiercely competitive market, food supply chains have become increasingly intricate, presenting common challenges such as traceability, safety, quality assurance, and overall trustworthiness. Consumers benefit from blockchain by accessing accurate and reliable information about food production and transactions. Blockchain facilitates easier interaction between consumers and producers, enabling consumers to understand the production process in depth. By streamlining goods exchange, blockchain strengthens consumer trust and confidence in food safety protocols. Adopting BCT helps establish trust with consumers and enhance product reputation by openly sharing detailed product information on the blockchain [5]. BCT holds promise for a wide range of applications in food cultivation and preparation. It ensures transparency and traceability throughout the supply chain, enhancing accountability. In addition to managing supply chains, BCT can improve financial transactions. Implementing BCT in the food industry improves supply chain management, reduces fraud, and minimizes food waste, thereby enhancing food safety and security. The transparency, efficiency, and security offered by BCT have the potential to significantly increase industrial productivity in food and agriculture production.

Effective supply chain management becomes essential due to challenges such as sudden spikes in demand leading to stock shortages. It also enhances customer satisfaction by ensuring smooth processes and product availability. Traditional supply chains, reliant on centralized systems like cloud databases and IoT(Internet of Things), suffer from issues like lack of transparency, security threats, and data integrity problems. Key drawbacks include inadequate food safety assurances, insufficient product origin information, transparency, and traceability issues, along with control limitations. Blockchain technology offers a solution by serving as a decentralized public ledger across a network. It ensures tamper-proof records, enhances security, and eliminates third-party intermediaries from transactions, thus reducing costs and improving product quality. The cryptographic methods used build trust among users and facilitate demand for products. Each block in the blockchain contains transaction details and links to the previous block through a hash value, maintaining a complete and secure ledger. The peer-to-peer network validates new transactions and users, using algorithms like Proof of Stake (POS) to ensure validity before adding transactions to the chain. Blockchain empowers small-scale farmers to trace their agricultural produce directly to customers, bypassing intermediaries and ensuring fair pricing. Furthermore, blockchain technology provides insights into market trends, ultimately boosting farmers' income. This collaboration is seen by ICRISAT (Intranational Crop Research Institute for Semi Arid Tropics) as the initial phase towards implementing blockchain technology in developing an E-agricultural system [5].

Food Safety and Quality Assurance

Food safety refers to the practices involved in the processing, handling, and storage of food to prevent illnesses among the population. With the global increase in trade, ensuring food safety and quality has become more challenging. Factors such as decreased trust, long transportation distances, complex supply chains, and extended processing times characterize today's food supply chains. Blockchain technology offers a promising solution to enhance traceability and transparency in food, addressing these critical issues effectively. Blockchain technology enables the tracking of food throughout its journey from farm to consumer, offering transparency to farmers and customers alike[6]. It helps in detecting any fraud that may occur along the supply chain. Additionally, blockchain ensures that farmers purchase verified agricultural inputs and monitors the subsidy distribution process. This technology provides a decentralized platform that enhances transparency, allowing both the government and farmers to trace transactions at every stage. As a result, blockchain appears to be a promising solution to the challenges encountered by the Indian agricultural sector.

Information stored on blockchain is immutable and accessible to all stakeholders, facilitating product traceability. Real-time food tracing systems utilizing blockchain technology create a platform where all members of the supply chain can access comprehensive information related to specific food items. This enhances openness, transparency, neutrality, reliability, and security within food supply chains. Blockchain captures detailed data about products at every stage, including details like pesticide use, artificial colourants, food additives, appearance, and environmental conditions such as temperature, humidity, and light, crucial for monitoring product safety and quality. Blockchain technology enables producers to establish trust with consumers and enhance the reputation of their products by providing transparent, individualized product information on the blockchain.

This transparency helps enterprises realize the full value of their products, thereby increasing their competitiveness. Consequently, fraudulent or low-quality product suppliers find it challenging to remain in the market, pushing all suppliers to improve product quality across the agricultural and food sectors. From the consumer's perspective, blockchain ensures access to accurate and reliable information about how food is produced and traded. This addresses consumer concerns regarding food safety, quality, and environmental impact. Blockchain also facilitates consumer-producer interaction by offering convenient and detailed insights into the food production process.

Crop Insurance

Weather extremes pose significant threats to agricultural production, jeopardizing food security. Both crop and livestock sectors are impacted, with climate change expected to intensify these challenges. Agricultural insurance has long been recognized as a crucial tool to manage these weather-related risks. Under traditional schemes, farmers pay premiums upfront before the growing season and receive payouts if they suffer losses due to adverse weather conditions. This arrangement shifts the financial risk to insurers, allowing farmers to mitigate their exposure to weather-induced financial losses. In cases where weather threats affect all insured farmers collectively, insurers can further hedge systemic risks with reinsurance companies. However, different types of agricultural insurances vary in how they assess losses and trigger payouts. Indemnity-based insurances, for example, reimburse farmers based on damage assessments conducted on-site by experts.

While precise in covering losses, these insurances are vulnerable to problems arising from asymmetric information. Farmers often possess more information about the risks and production practices than insurers, leading to issues such as adverse selection and moral hazard. Adverse selection means higher-risk farmers are more likely to seek insurance, while moral hazard may prompt farmers to adopt riskier practices once insured. These factors can undermine the effectiveness of indemnity-based schemes, necessitating measures like deductibles to mitigate them. Additionally, certain agricultural productions like grazed meadows cannot be insured due to measurement challenges[7].

To address the drawbacks of indemnity-based insurances, index-based insurances have emerged as an alternative or complement. Here, payouts are not based on actual losses but on predefined indices, such as rainfall data from nearby weather stations. This approach aligns the information available to both farmers and insurers, eliminating issues of adverse selection and moral hazard. It also simplifies the payout process, enabling timely and automated payments following a verified adverse weather event. However, there is a risk of basis mismatch between the index and actuate Managemental on-farm losses, termed basis risk. Basis risk can stem from spatial differences, temporal mismatches, or design flaws in the index determination process.

Index insurances are increasingly crucial for farmers as they offer comprehensive risk management while efforts are focused on reducing basis risk[8]. Blockchain technology has shown promise in enhancing index insurances by enabling automated and timely payments based on predefined conditions in smart contracts. Smart contracts can integrate diverse data sources such as weather information, plant growth data, and farm machinery data through smart oracles, thereby improving the accuracy of index determination and payout processes. Several initiatives, like those by Etherisc, WorldCover, and Arbol, are already exploring blockchain based smart contracts for crop insurance, utilizing cryptocurrencies like Ether for payouts. Despite the advantages of decentralized blockchain-based insurances, challenges remain. Farmers, particularly in developing regions, may lack access to the necessary infrastructure to participate effectively. To address this, solutions such as third-party payment gateways and integrations are being proposed to facilitate participation without requiring direct cryptocurrency ownership.

Smart Contract

Blockchain technology offers significant advantages over traditional contracts, especially in industries like supply chain management where paper documentation can lead to inefficiencies and security risks such as theft. Smart contracts, a cornerstone of blockchain technology, address these drawbacks by automating processes based on predefined conditions. Unlike traditional contracts, which may require intermediaries and manual oversight, smart contracts are self-executing pieces of code that facilitate actions such as payments immediately upon meeting contract terms. This capability distinguishes platforms like Ethereum from others in the blockchain space. For instance, in a supply chain scenario, a smart contract can automatically release payment to a carrier once a customer confirms receipt of their parcel. By eliminating the need for intermediaries, smart contracts reduce time, effort, and costs associated with transactions, while minimizing the potential for human error or fraud.

Smart contracts function as digital promises between transaction parties, holding each accountable for their respective roles without relying on traditional contract enforcement mechanisms. They enhance supply chain transparency, traceability, and efficiency, thereby fostering stronger relationships among stakeholders. Each smart contract is uniquely identified by a 20-byte address and once deployed on the blockchain, its code remains immutable ensuring that transactions sent to the contract address are executed by consensus across the network. There are two main types of smart contracts: deterministic and non-deterministic. Deterministic smart contracts execute independently without external information, whereas non-deterministic smart contracts rely on external data or databases to fulfil their conditions.

Smart Agriculture

Smart agriculture is characterized by the use of information and communication technology (ICT), the Internet of Things (IoT), and modern data collection and analysis technologies like unmanned aerial vehicles (UAVs), sensors, and machine learning. A crucial aspect of establishing smart agriculture is developing a comprehensive security system for data use and management. Traditional data management methods are centralized and susceptible to inaccuracies, distortion, misuse, and cyber-attacks. For instance, environmental monitoring data is often managed by centralized government entities, which may have their own interests and can influence decision-making related to the data. Blockchain technology offers a way to store data and information generated by various actors and stakeholders throughout the entire value-added process, from seed to sale, in the production of agricultural products. It ensures transparency for all involved parties and makes the recorded data immutable. Different types of blockchain (permissioned or permissionless) on platforms like Ethereum or Hyperledger, along with consensus mechanisms such as Proof of Work, Proof of Stake, and Practical Byzantine Fault Tolerance, might be suitable for collecting data and information at various stages in crop agri-food systems. Blockchain provides security through decentralization, unlike traditional technologies that rely on "security through obscurity" (IBM Institute for Business Value, 2015). Distributing data to stakeholders' computers is less vulnerable to loss and distortion compared to centrally managed servers.

A blockchain is a database containing timestamped batches of transactions and activities related to a product. This decentralized storage is more secure than centralized servers managed by administrators. The database is also valuable for developing data-driven mobile applications to optimize farming. Moreover, blockchain addresses the challenge of creating a secure infrastructure for IoT and integrating various technologies used in ICT e-agriculture. Many smart farming models have been proposed and implemented based on the combined use of IoT and blockchain technology. For example, Patil, *et al,* (2017) [9] propose a "lightweight blockchain-based architecture for smart greenhouse farms," where IoT sensors act as a private local blockchain managed by the owner. Lin, *et al,* (2017) [10] propose a blockchain and IoT-based smart agriculture framework for general use, with a platform at its core that helps establish trust among actors using blockchain. Agents involved in the product lifecycle, from planting to sale, can access the data stored in the blockchain via smart mobile devices. Lin, *et al,* (2017) [10] propose a blockchain-based ICT e- agriculture model for local and regional use, where each actor has access to real-time water quality data stored in the blockchain.

Many companies are investing in blockchain applications for smart agriculture. For instance, the company Filament provides devices for connecting physical objects and networks using smart farming technology. They have developed penny-sized hardware that can be easily used with existing machines or devices through any USB port to securely transact with a blockchain. Blockchain is also used by farm organizations to enhance their farming practices. In Taiwan, farmland irrigation associations use blockchain to collectively archive data and interact with the public more effectively [10]. Each association acts as a "public juridical person" and publishes their data and information about irrigation management on the blockchain, accessible to the public. This transparency encourages public involvement in irrigation management and efforts to improve water resource use. Over time, the longitudinal database created using blockchain can inform decision-making on the construction and maintenance of irrigation canals. While smart agriculture with blockchain does not necessarily lower the technological barriers for farmers, it may, in fact, raise them. It is more likely to collect reliable data from large farmers than from smallholders for uploading to the blockchain. Large farmers are more inclined to participate in blockchain-based smart agriculture and benefit from it, potentially widening the gap between large farmers and smallholders.

Process of Blockchain Technology

The Provider-Consumer Solution enhances the efficiency of blockchain as a database structure by utilizing a public ledger that contains digital information about products, individuals, or events. This ledger is accessible and inspectable by numerous users. Blockchain technology offers several advantages, such as:

Enhanced transparency
Reduction of errors
Prevention of product delays
Elimination of unethical and illegal activities
Improved management
Increased trust between consumers and suppliers

As customer demands rise, there is a need for an optimized supply chain, and blockchain technology can significantly enhance supply chain management and marketing. Suppliers can upload data about food products, including harvest dates and prices.

These products are then tagged with RFID chips, which can be placed on various items, from individual parts to delivery labels. RFID tags contain a microchip and antennae, and specialized printers can wirelessly load identifying i(Radio Frequency Identifier) information onto these tags.
RFID scanners read information from the tags, which can include:
ID numbers
Serial numbers for individual products
Location logs
Bin locations of products
Order statuses
Components of the products
RFID data is matched with the system to track shipments and stock locations automatically as products move through warehouses and trucks. Implementing RFID in these systems ensures the correct products and quantities are collected at each point, reducing errors. Combined with IoT, product information can be tracked throughout shipment and storage, enhancing accuracy, efficiency, and accountability. An RFID-enabled supply chain network can determine a product's location, allowing for immediate detection and enforcement against theft and other illegal activities. Once suppliers attach RFID tags, producers receive information about the food product and add a QR code to the packaging. As the product moves from producer to distributor, the distributor automatically receives notifications about the receipt of food products. Distributors then select suitable Third-Party Logistics (3PL) providers based on comprehensive data on customers, delivery dates, and other relevant information[11]. 3PL providers, which offer distribution, warehouse, and fulfillment services, are informed about the origin and destination of the food products and flexibly optimize network flows.
Retailers use machine learning-based forecasting and provide an app for end customers. The product information remains consistent as the product moves to market, ensuring full transparency on delivery times. Retailers can adapt orders, promotions, and other activities accordingly. All transactions occur within smart contracts. At each stage of production, organizations scan the RFID tags and update details using a mobile app, with the data stored in the cloud. The cloud plays a crucial role in storing blockchain data, with verification, validation, and transactions conducted through the app or website. A mobile app and website serve as communication platforms. Blockchain technology initiates with the creation of the genesis block, where details are stored, and the first transaction is recorded. Customers can scan the QR code via the app to view product details, including origin, aging, duration, and expiry.

Case Studies and Examples

AgriDigital

AgriDigital is an integrated commodities management platform designed for the global grains industry, utilizing Ethereum blockchain technology to enhance transparency and efficiency. This innovation aims to rebuild trust among farmers by facilitating real-time payment settlements through blockchain, thereby eliminating seller counterparty risks. The platform strives to streamline the global supply chain, offering simplicity, accessibility, and security. Accessible via computers, tablets, or smartphones, AgriDigital comprises five core modules:
Transactions: Facilitates easy buying, selling, and logistics management for farmers and stakeholders.
Storage: Digitally stores crucial information such as payments, orders, deliveries, and inventory securely.
Connections: Expands connections between farmers and customers, fostering broader business networks.
Finance: Executes financial transactions and facilitates virtual currency transfers between farmers and consumers.
Remit: Automates remittances to farmers upon completion of transactions.
Blockchain integration ensures real-time payments, democratizes access to supply chain financing, and provides consumers with provenance data for informed purchasing decisions. By recording farming, production, transportation, and delivery data on the cloud, AgriDigital addresses food fraud and enhances supply chain security. Notifications keep farmers informed about their transactions, ensuring transparency throughout. AgriDigital introduced digital tokens representing physical commodities on the blockchain, establishing digital trust among supply chain participants. As the pioneer in live settlement of physical products on blockchain, AgriDigital operates globally with 300 active users across 30 countries. Its contributions to agribusiness include:
Connecting local farmers to the global supply chain.
Real-time tracking of grain sales between growers and buyers for transparent supply chains.
Real-time payment settlements via smart contracts, eliminating credit risks to growers.
Providing comprehensive trade flow management, funding access, and traceability of product origins for customers.
AgriDigital empowers users with efficient trade management, financial access, and traceable product origins.

TE-FOOD

TE-FOOD operates as a blockchain-based traceability system for the farm-to-table journey of food, ensuring transparency and accountability across the supply chain. The FoodChain, its public permissioned blockchain, allows participants including consumers to maintain master nodes, decentralizing traceability data. Key goals include enhancing consumer trust, improving operational efficiency, adhering to export regulations, combating counterfeit products, and facilitating swift product recalls. TE-FOOD employs various tools and applications:
Identification Tools: Utilizes barcodes, RFID tags, security seals, and label stickers to track physical objects. software.
National Livestock Management Solutions: Offers systems for managing livestock, enforcement, and administration.
Farm Management Tools: Provides category-specific tools for farm operations like vaccination, feeding, and fertilization.
Food Safety Tools: Features fraud management systems, food condition sensors, and meat quality analysis tools.
TE-FOOD offers implementation models for private entities and institutions, enabling either individual or collective traceability efforts. It uniquely supports B2B, B2C, and B2A services, benefiting businesses, consumers, and regulatory bodies. By allowing consumers to trace food origins and processing details, TE-FOOD builds trust and aids in early contamination detection, preventing foodborne illnesses. It also enhances regulatory oversight by providing real-time market insights. However, TE-FOOD faces challenges such as the relatively low transaction speed of its TFD token on the Ethereum network (15 TPS) and competition from companies like AMbrosus, WABI, MOD, and WTC. Despite these challenges, TE-FOOD remains a comprehensive solution for implementing food traceability, ensuring end-to-end visibility and process control across the supply chain.

Ripe.io

Ripe.io, established in 2017 in the United States, specializes in utilizing blockchain technology to track food through its "Blockchain of Food" network. This innovative approach aims to provide consumers with comprehensive information about food origins, growing conditions, delivery details, and other relevant data using blockchain, IoT, AI, and machine learning technologies. Collaborating with R3's Corda blockchain platform, Ripe.io focuses onenhancing transparency and trust within the agricultural supply chain. Currently offered as software-as-a-service, Ripe.io plans to evolve into a fully licensed API and transactional product over time[12]. The core objective is to re-establish connections within the supply chain by documenting the journey of products, thereby promoting transparency throughout. The system employs a software stack with blockchain as its foundation, complemented by hardware solutions for data integration via sensors, effectively creating a "food internet."
Data collection across the food supply chain involves recording information on a blockchain ledger, sharing it securely with supply chain stakeholders, and validating its authenticity while safeguarding privacy. Blockchain facilitates secure information exchange among all participants, ensuring the quality and integrity of food as it progresses through the chain.

Integration of IoT allows for real-time monitoring of variables such as temperature, humidity, and other critical factors, contributing to digital and secure data storage without human error. Ripe.io's impact on the agriculture industry includes empowering consumers with access to detailed information about crop origins and production conditions. For farmers, it enables efficient monitoring of essential variables like temperature and humidity, crucial for maintaining crop quality. The system records and shares crop quality levels across the supply chain, ensuring food safety and security for all stakeholders.

However, Ripe.io faces challenges such as potential performance issues due to continuous data streaming from IoT devices and blockchain's limited throughput because of its complex cryptographic protocols. Additionally, there are challenges related to trust and adoption of blockchain technology, given its novelty and evolving nature, as well as interoperability issues when transitioning from legacy systems to blockchain solutions, which require additional costs and expertise.

AgriLedger

AgriLedger is a social entrepreneurship initiative aimed at empowering agricultural farmers through mobile applications built on R3's Corda blockchain platform. Launched in 2019, it introduced a blockchain ecosystem in Haiti to enhance supply chain transparency and ensure fair pricing for suppliers and retailers[12]. The core mission of AgriLedger is to facilitate small farmers' access to global markets and financial services via API (Application Programming interface) links with local banks and institutions.

The mobile application focuses primarily on traceability and payment processes, allowing producers to maintain ownership until final sales. Key features include:

Digital Identity: Each participant in the supply chain, including farmers, receives a unique digital identification number upon registration. This enhances their recognition within the supply chain, improving access to financial, insurance, logistical, and other essential services.

Asset Digitization: Agricultural assets such as rice or coffee can be digitized through tokenization. This process enhances liquidity, facilitates peer-to-peer trading, and increases the overall value of agricultural commodities markets.

Immutable Data: Information stored on the distributed ledger technology remains immutable, ensuring trust, transparency, and traceability across the entire supply chain.

Record Keeping and Financial Access: The digital ledger provides robust record-keeping capabilities and proof of income, enabling farmers to access finance loans and other financialservices. A digital wallet feature allows for direct deposits from financial institutions and facilitates faster payments from buyers to farmers, thereby improving supply chain efficiency.

For instance, a farmer in Haiti can digitally register and track 500 mangoes delivered to a collection point. Each stage of the journey, from collection to delivery in Port-au-Prince and subsequently to a US supermarket, is recorded in blocks on the blockchain. Customers can scan QR code stickers to learn about the mangoes' journey, and farmers receive SMS notifications upon their sale.

AgriLedger has significantly impacted rural farmers in poor and developing countries by:

Providing accurate and verifiable record-keeping, ensuring fair and prompt payments postsales.

Lowering production costs through resource sharing and collective purchasing power.

Granting digital identities to small farmers, enabling access to financial services such as banking and loans, thereby increasing income by up to 50% and addressing issues of financial inclusion.

Opening doors to global agricultural markets for small farmers who previously struggled to reach even local markets.

Despite these benefits, AgriLedger faces challenges such as ensuring the security of farmers' private keys, especially against unauthorized transactions. It also encounters usability issues among illiterate farmers and infrastructure challenges in remote areas, including access to electricity for mobile charging, internet connectivity, and network coverage. These obstacles highlight areas for improvement as AgriLedger continues to evolve and expand its impact on agricultural communities worldwide.

Etherisc

Etherisc is an open-source development platform specializing in decentralized crop insurance applications built on blockchain technology. The company develops blockchain-centric solutions for various sectors within the insurance industry. In 2019, Etherisc successfully piloted its blockchain crop insurance solution in Sri Lanka in collaboration with Aon and Oxfam, aimed at reducing and effectively covering agricultural risks[12]. Additionally, Etherisc partnered with Chainlink in November 2020 to introduce crop insurance in Kenya, focusing on automatically triggering insurance payouts during extreme weather events. Etherisc's crop insurance solution is based on its Ethereum-based "Generic Insurance Framework," which utilizes local meteorological data as input for smart contracts. Chainlink's decentralized oracle network ensures secure and reliable connections to external weather data sources, broadcasting information to smart contracts for independent verification by all parties involved.

In case of extreme weather conditions, insurance policies are automatically triggered based on input data, ensuring fair, timely, and transparent payouts that are resistant to tampering or alteration by insurers. Users select their agricultural product and field location in the Crop Insurance Application, pay Ether to a DAPP (Decentralized Application or "smart contract"), and receive immediate payouts in the event of droughts or floods. Smart contract algorithms verify GPS and weather station data specific to farmers' field locations, allowing Etherisc to assess risks and contract conditions efficiently at the outset, and manage claims over time. This automated process saves insurers time and money, reduces labor-intensive procedures, minimizes the risk of human error, and helps prevent fraud, thereby streamlining claim payouts.

Etherisc's blockchain-based crop insurance solution has had a positive impact on the agriculture industry by:

Automating payment triggers based on weather data, eliminating the need for farmers to file claims, thus simplifying processes and enhancing transparency.

Automatically initiating insurance policies based on weather data inputs, reducing the risk of human error and fraudulent activities during payout processes.

However, Etherisc faces several challenges with its crop insurance solution:

Basis risk stemming from poorly designed indices, discrepancies between index measurement sites and actual production fields, and the variability and unpredictability of covered regions.

Risks associated with data tampering at weather stations used for index calculations, which can favor involved companies.

Insufficient availability of adequate weather stations and reliable data, which impacts the successful implementation of weather-based crop insurance solutions.

Secure Data Transmission Using Blockchain Technology

Recent advancements in Blockchain technology offer a promising solution to address critical flaws in current technical systems. Blockchain simplifies and enhances accessibility across interconnected profiles and processing application schemas. According to recent assessments by resarchers, blockchain's technological impact and applications are substantial, particularly in resolving the interdependent nature of system operations and enabling traceability of past transactions[13]. While Blockchain aims to revolutionize various domains like networking, IoT, and business transactions, security remains a significant concern. Researchers are actively tackling complexities and security challenges at the physical layer of Blockchain application. There is a noted demand in information-centric processing systems, which Blockchain directly addresses. Innovators propose an Information Centric Network (ICN) that incorporates trust dependencies for secure data transactions. This architecture first computes human interaction behavioral models for data filtering in transmission lines before assessing trust factors for transactions, aiming to improve content discovery.

Furthermore, efforts are underway to handle client inquiries efficiently, focusing on content relevance and stable query handling. An example is the Social-network-Aided Efficient Live Streaming System with High Profitability and Adaptability (SAVE), which monitors customer communication channels, collects data on message interactions, and optimizes system performance, thereby reducing server load.

Authors in emphasize the importance of fair resource allocation among peers to optimize replication strategies for serving client requests. Their proposed Fair Sharing with Bounded Degree model determines the optimal number of peers required for efficient service delivery based on planning. In addressing bandwidth allocation issues in P2P networks, researchers propose using multiple overlays to assess data transmission capabilities and optimize ISP traffic savings. They recommend methods for coordinating peer groups and increasing ISP traffic savings in BitTorrent systems, citing significant improvements in download times under realistic conditions.

Additionally, researchers explore governance strategies to ensure Quality of Service (QoS) in P2P networks, focusing on contract-based interactions between end users and peers to mitigate issues like free-riding. Their work aims to predict future demands of client companions and providers, utilizing cosmology-based indexing to enhance discovery of P2P SCC configurations. In summary, recent research highlights Blockchain's potential to enhance system reliability, security, and efficiency across various technical domains, albeit challenges remain in implementation and scalability. These advancements pave the way for transformative applications in decentralized and information-centric networks.

Limitations

Blockchain technology facilitates traceability in the food supply chain, enhancing food safety by securely storing and managing data. This technology supports the development of datadriven innovations for smart farming and index-based agriculture insurance. It also has the potential to lower transaction costs, thereby improving farmers' market access and creating new revenue opportunities. Despite these benefits, significant challenges persist in applying blockchain in agriculture and food sectors. One critical area needing further exploration is understanding why transacting parties would truthfully and accurately input information into the blockchain ledger, especially in contexts such as smallholder farming where data is decentralized among individual farmers[14]. The benefits of blockchain for farmers may vary depending on farm size. Smaller farms, for example, could more readily participate in blockchain-based insurance markets, whereas larger farms might find it easier to collect and integrate on-farm data. Future research should assess which types of farms stand to gain or lose from blockchain solutions.

Another challenge to adopting blockchain technology in the agriculture sector is the high cost associated with acquiring the necessary data for the blockchain ledger. While setting up the distributed ledger itself may be relatively inexpensive, gathering the specific data required, such as DNA information for livestock, can be prohibitively costly. Although sampling methods can mitigate these expenses, they necessitate a large population of products for data collection, posing a greater burden on smaller farms compared to larger ones and potentially exacerbating income disparities. Additionally, integrating blockchain with existing legacy systems presents another hurdle. Successful implementation requires seamless connection with databases and systems like enterprise resource planning, warehouse management, and manufacturing execution systems. Establishing this infrastructure is often time-consuming, requiring middleware and communication protocols to effectively integrate blockchain with established technologies.

Challenges in the Agricultural Supply Chain and Blockchain Implementation

The main challenge in the agricultural supply chain is efficiently transporting products from farmers to consumers. While blockchain technology offers a secure and transparent method to track the movement of agricultural goods, it cannot address the issue of damage during transport or detect falsification at the initial data entry stage. Blockchain can help reduce fraud and corruption in the supply chain, but it remains vulnerable to attacks from intruders, hackers, and viruses, which necessitates further research. Although blockchain can provide a continuous record of quality data and track food movement from farm to table, it cannot proactively prevent data falsification. It can reduce food adulteration by continuously recording untampered processing data but lacks early-stage tampering prevention mechanisms. There are both technical and technological challenges in implementing blockchain in agriculture, as well as the need for adoption by other stakeholders. The technical challenges include:

The agricultural sector has complex, uncaptured legacy rules with fragile connections that are difficult to translate into binary logic for blockchain adoption.

The unpredictability of nature, which directly affects the agricultural supply chain, complicates attribute-based decision-making and leads to reluctance in adopting blockchain.

Additional processes and compliance requirements for data management, along with issues related to data ownership and retention within the blockchain, add to the overhead.

Interoperability issues and seamless data transfer between blockchain and legacy systems remain unresolved.

Scalability challenges arise with larger implementations and deployments.

The significant energy and financial costs associated with blockchain usage present financial challenges.

SWOT Analysis

Swot analysis is a tool for evaluation of the strengths, weakness, opportunities and threats for a project or a venture, here is the possible SWOT analysis for the use of blockchain technology in agriculture sector.

Strength - Blockchain technology has the capability to enhance transparency and traceability in supply chains, addressing a significant challenge in the agriculture sector. It has the potential to lower transaction expenses and improve market entry opportunities for small-scale farmers. Both within India and internationally, there is increasing enthusiasm for employing blockchain technology in agriculture[15].

Weakness - Introducing blockchain technology into agriculture necessitates substantial investments in technology, education, and skill development. There is a shortage of technical know-how and governmental backing for blockchain-driven agricultural initiatives.

Additionally, there is insufficient empirical data on how blockchain technology influences critical metrics such as crop yields and farmer incomes.

Opportunities - The integration of blockchain technology in agriculture holds promise for delivering substantial advantages to farmers, consumers, and other involved parties. The increasing call for traceability and openness in the global food supply chain presents opportunities for applying blockchain technology in agriculture. Both within India and worldwide, there are multiple governmental and private sector efforts aimed at promoting the adoption of blockchain technology in the agriculture sector.

Threats - The utilization of blockchain technology in agriculture could potentially face security concerns, such as vulnerabilities to data breaches or cyber-attacks. Technological obstacles or restrictions, such as the necessity for fast internet access or specialized hardware, may hinder the adoption of blockchain technology in the agricultural domain. Additionally, social or cultural impediments, like limited awareness or comprehension of the technology among farmers and other stakeholders, could also impede its adoption in agriculture [16,17].

Conclusion

The integration of blockchain technology into agriculture holds considerable promise for transforming the sector by enhancing transparency, traceability, and efficiency across supply chains. Key areas of application include crop insurance, supply chain management, and smart agriculture. These applications offer numerous benefits such as reducing fraud, ensuring timely payments, and improving data accuracy and security. Blockchain's immutable ledger ensures transparent and traceable records of agricultural products from farm to table, enhancing food safety and consumer trust. Smart contracts automate processes based on predefined conditions, reducing the need for intermediaries and minimizing errors and fraud. The integration with IoT devices and advanced technologies enables real-time data collection and analysis, optimizing farming practices and resource management. Blockchain also facilitates real-time payment settlements and democratizes access to supply chain financing, empowering small farmers to participate in global markets. Several case studies illustrate these benefits. AgriDigital enhances transparency and efficiency in the grains industry through real-time payment settlements and comprehensive supply chain management.

TE-Food provides a blockchain based traceability system for the entire food journey, improving operational efficiency and regulatory compliance. Ripe.io utilizes blockchain, IoT, AI, and machine learning to offer detailed information about food origins and conditions, promoting transparency. AgriLedger empowers farmers through mobile applications, ensuring fair pricing and improving access to financial services. Etherisc offers decentralized crop insurance applications that automate insurance payouts based on weather data, reducing risks and enhancing transparency.

However, several challenges and limitations need to be addressed. High costs associated with acquiring the necessary data for blockchain implementation can be prohibitively expensive, especially for small farmers. Reliable internet access, specialized hardware, and integration with legacy systems are essential for successful blockchain adoption. Additionally, vulnerabilities to data breaches and cyber-attacks pose significant risks. Limited awareness and understanding of blockchain technology among farmers and stakeholders can hinder adoption. To fully realize the potential of blockchain in agriculture, further research and development are necessary. Key areas for future exploration include improving data collection methods to ensure accurate and comprehensive blockchain records, enhancing interoperability to create seamless integration with existing systems and databases, addressing security issues to protect against cyber threats, and increasing awareness and education through training programs and initiatives to enhance understanding and acceptance of blockchain technology among farmers and stakeholders.

Application of research: Blockchain technology presents significant opportunities for the agricultural sector, addressing the associated challenges and limitations is crucial for its successful implementation and widespread adoption. By leveraging blockchain's strengths in transparency, traceability, and efficiency, the agriculture industry can achieve substantial improvements in supply chain management, food safety, and market access, ultimately benefiting farmers, consumers, and all stakeholders involved.

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