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ARTICLE REVIEW

IMPACT OF BLOCKCHAIN TECHNOLOGY IN AGRICULTURE SUPPLY CHAIN A COMPREHENSIVE REVIEW OF APPLICATIONS, CHALLENGES, AND FUTURE DIRECTIONS

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ABSTRACT

Purpose: This review paper examines the transformative potential of blockchain technology in addressing critical challenges within agricultural supply chains, including traceability, transparency, fraud prevention, and equitable value distribution. It aims to synthesize existing research and real-world applications to highlight how blockchain can create more efficient, sustainable, and fair food systems.

Methodology/Approach: The study adopts a systematic literature review methodology, analyzing peer-reviewed articles, industry reports, and case studies from 2008 to 2024. Key frameworks and implementations, such as IBM Food Trust, AgriDigital, and TE-FOOD, are evaluated to identify patterns, benefits, and limitations of blockchain adoption in agriculture.

Originality/Relevance: This paper contributes to the growing body of research on blockchain in agriculture by integrating insights from decentralized finance (DeFi), IoT, and AI, offering a holistic view of next-generation supply chains. It addresses gaps in scalability, regulatory challenges, and adoption barriers while proposing future trends like tokenization and predictive analytics.

Key Findings: Blockchain enhances traceability, reducing food fraud and enabling rapid contamination tracking (e.g., Walmart's mango traceability in 2.2 seconds). Smart contracts automate payments and compliance, empowering smallholder farmers with timely compensation. Integration with IoT and AI improves real-time monitoring and demand-supply matching, fostering sustainability. Challenges include scalability limitations, regulatory ambiguities, and the digital divide in rural areas.

Theoretical/Methodological Contributions: The paper advances theoretical understanding by linking blockchain to ethical sourcing, sustainability, and farmer empowerment. Methodologically, it provides a framework for evaluating blockchain's role in multi-stakeholder supply chains, emphasizing hybrid architectures and decentralized verification. The findings underscore blockchain's potential as a foundational technology for equitable and resilient food systems.

Keywords: Blockchain. Agri-Supply Chains. Smart Contracts. Traceability. Sustainability. IoT. Decentralized Finance (DeFi)

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1. INTRODUCTION

Blockchain is a transformative digital ledger technology that offers a decentralized, secure, and immutable system for recording transactions across a distributed network. At its core, blockchain creates a chronological chain of data "blocks" that are cryptographically linked and verified by network participants, eliminating the need for centralized control or intermediaries. This technology is particularly well-suited to address long-standing challenges in agricultural supply chains, which have traditionally suffered from opacity, inefficiency, and trust issues among (Kamilaris et al., 2019) stakeholders.

1.1 Definition of Blockchain and Its Relevance to Agri-Supply Chains

In agricultural applications, blockchain establishes complete traceability throughout the supply chain. Each product can be assigned a unique digital identifier that records every step of its journey - from seed planting and harvest conditions to processing, transportation, and retail distribution. This granular tracking capability was powerfully demonstrated by Walmart's blockchain implementation, (Mao et al., 2022), (Caro et al., 2023) which reduced the time needed to trace mango origins from seven days to just 2.2 seconds. Such traceability not only improves food safety by enabling rapid identification of contamination sources but also combats pervasive issues like food fraud, where products may be mislabeled (e.g., conventional produce sold as organic) or adulterated.

The technology's smart contract functionality automates critical supply chain processes. These self-executing digital contracts trigger actions like payments to farmers when predefined conditions are met (e.g., delivery verification or quality certification), addressing chronic payment delays that smallholder farmers frequently face. Platforms like AgriDigital have successfully implemented this for grain transactions, ensuring timely compensation while reducing administrative overhead (Saberi et al., 2024). For sustainability initiatives, blockchain provides verifiable proof of ethical sourcing practices and environmental impact. It can track carbon footprints throughout production and distribution, validate fair trade certifications, and monitor compliance with regenerative agricultural practices. This level of transparency meets growing consumer demand for responsibly produced food while helping producers command premium prices.

However, significant adoption barriers remain. The technology requires substantial digital infrastructure in often connectivity-challenged rural areas. Many farmers lack the technical literacy to interact with blockchain systems, and questions persist about how to scale the technology cost-effectively for diverse agricultural sectors. Current implementations also reveal challenges in data standardization and interoperability between different blockchain platforms. Looking forward, the integration of blockchain with complementary technologies like IoT sensors (for real-time condition monitoring) and AI (for predictive analytics) promises to create even more robust and intelligent agricultural supply chains. As demonstrated by pioneers like IBM (Zheng et al., 2024) Food Trust and the World Economic Forum's blockchain initiatives, when these implementation challenges are addressed, blockchain has the potential to fundamentally transform agricultural supply chains into more transparent, efficient, and equitable systems that benefit all stakeholders from farm to consumer.

1.2 Key challenges in traditional agriculture supply chains

Traditional agricultural supply chains suffer from deep-rooted inefficiencies that create systemic barriers across the entire value chain. The fundamental challenge stems from fragmented information flows and lack of transparency, where stakeholders operate in isolated silos without real-time data sharing, making it nearly impossible to track product origins or verify quality claims accurately. This opacity breeds multiple problems: smallholder farmers face severe financial disadvantages, often receiving just a fraction of the end-product value while waiting months for payments through convoluted intermediary networks. Simultaneously, the absence of coordinated logistics and (Kshetri, 2021), (Tian, 2017) temperature-controlled infrastructure results in staggering post-harvest losses, particularly in developing economies where up to 40% of produce never reaches markets. Supply chain complexity further compounds these issues, with excessive handling and paperwork adding 15-20% to operational costs while increasing the risk of quality deterioration. Perhaps most troubling are the sustainability and ethical concerns that persist unchecked, from deforestation-linked commodities to documented cases of child labor in cash crop production, all enabled by the current system's inability to provide auditable proof of ethical sourcing. These structural weaknesses are exacerbated by vulnerable certification systems where paper-based records remain susceptible to fraud, undermining consumer trust in premium product claims. Together, these interconnected challenges create an agricultural supply chain paradigm that is simultaneously inefficient, inequitable, and unsustainable - wasting billions in economic value annually while failing both producers and consumers. The magnitude of these issues highlights why digital transformation through technologies like blockchain is increasingly viewed not just as an optimization tool, but as a necessary foundation for building resilient, transparent, and fair global food systems.

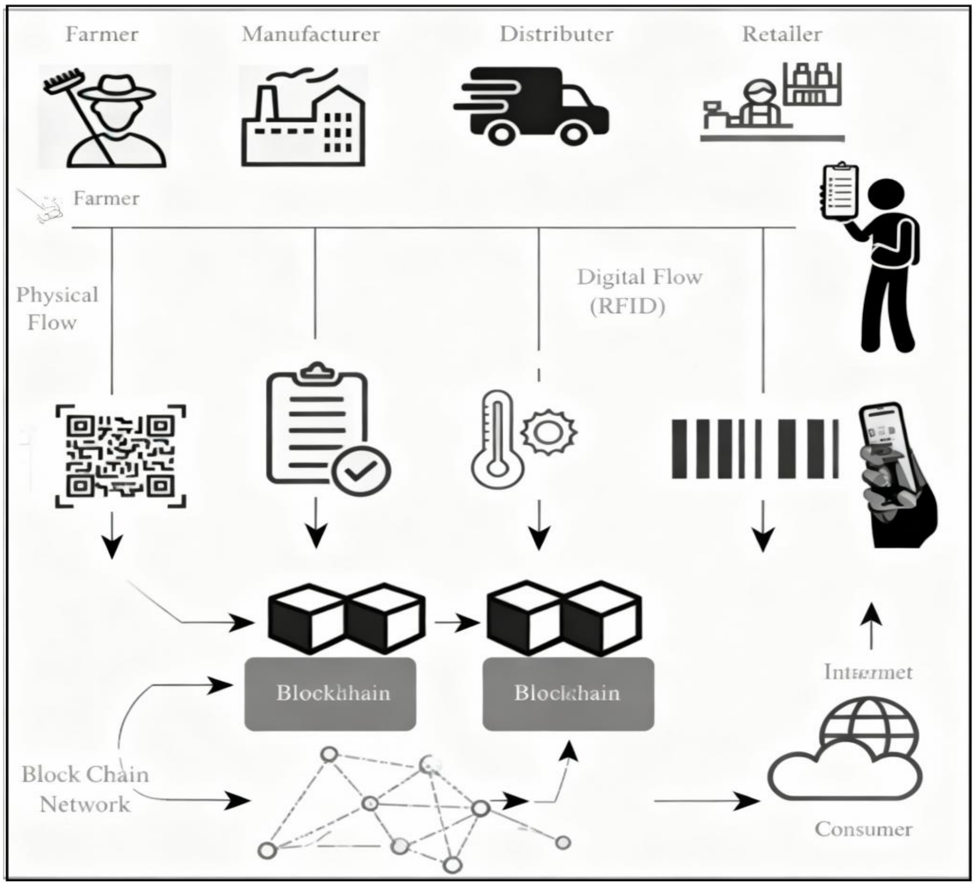

Fig 1: Linear Supply Chain using Blockchain

Figure 1 illustrates a standard linear supply chain of farmers, manufacturers, distributors, retailers, and consumers that is augmented with a parallel digital tracking system. Physical products, whether they be crops or packaged goods, flow from left to right while real-time data is collected based on RFID tags, IoT sensors, or mobile apps at each node and documented on a blockchain network. This decentralized ledger is internet accessible and reflects tamper-proof transparency because it records permanent information including origins, processing procedures, storage conditions, and transportation history. In this context, the farmers logging harvest data through a mobile app, the manufacturers adding quality certifications, the distributors updating shipping conditions, and the retailers confirming freshness are all information that consumers can access via a QR code scan. The blockchain layer (Lin et al., 2018) acts as the source of truth to bridge gaps between participants who previously operated as independent silos across their own supply chains. Blockchain provides less room (Tripoli & Schmidhuber, 2018) for fraudulent intent, improves traceability, and even allows for the automatic generation of smart contracts (where products are paid for or compliance is verified without human oversight). The physical and digital supply chain flow you see here exemplifies how blockchain introduces new levels of accountability and efficiency to a once fragmented supply chain and puts the consumer in front of that chain. According to Kamilaris et al. (2019), there is a substantial discrepancy between blockchain's theoretical potential and its actual scalability. According to their research, one of the main obstacles to widespread adoption of blockchain technology is its inability to handle the massive volumes of data that are typical of global agri-food supply chains. The question of whether blockchain is a game-changing "silver bullet" or just an auxiliary tool that needs to be a part of a larger suite of traceability technologies is brought up by this. In a continous analysis, Pearson et al. (2019) contend that blockchain is frequently heralded as a food traceability miracle without a thorough critical assessment of its real-world constraints. They stress that a significant gap exists in the economic viability of implementation, especially for smallholder farmers who must pay high prices for IoT sensors and blockchain integration while consumers and retailers benefit the most. The authors also highlight a major governance issue, pointing out that most jurisdictions still have unclear laws governing smart contracts, leaving stakeholders without a clear path forward in the event that automated agreements fail. This raises concerns about the technology's suitability for mission-critical applications. The boundary conditions for blockchain's utility are one of the main conceptual differences noted by Behnke & Janssen (2020). They contend that blockchain is not a one-size-fits-all solution and is only useful in supply chains where fraud or mistrust impedes transparency (Behnke & Janssen, 2020). Their research also sheds light on a significant debate in data governance: private blockchains, which are frequently run by a single, influential group, essentially reintroduce centralization, undermining a fundamental tenet of the technology, while public blockchains have the potential to reveal commercially sensitive data.

Feng et al. (2020) discuss important adoption and technical issues. According to Feng et al. (2020), there is a conflict between the technology and the sustainability objectives it seeks to promote because energy-intensive consensus mechanisms like Proof of Work are not environmentally sustainable for agriculture. Stakeholder resistance is a significant adoption gap that is mostly caused by farmers' low digital literacy and an incentive misalignment. The authors also reveal a conceptual difference in priorities: end users along the supply chain place a higher value on affordability, ease of use, and observable, instant advantages than do technology developers, who concentrate on sophisticated features like cryptographic security. Saberi et al. (2024) examine new issues and debates surrounding equity and sustainability. They point out that there is a research gap in the way blockchain can support a circular economy, as its capacity to track waste and encourage reuse has not received enough empirical attention (Saberi et al., 2024). Their research sparks a debate about social justice, pointing out that if smallholder farmers are denied access to data or are unable to engage with the digital system, blockchain may worsen already-existing disparities. Additionally, they point out a basic conceptual conflict between the decentralized nature of blockchain technology and its actual implementation, which is frequently spearheaded by big agribusinesses and may actually strengthen rather than challenge their market dominance. The comparative analysis of Agriculture Supply chain using Blockchain in various countries is shown in table 1.

Table 1: International Comparative Analysis of Blockchain in Agriculture

Region	Key Focus & Drivers	Notable Case Studies / Applications	Key Challenges	Unique Value Proposition
Africa	Farmer empowerment, financial inclusion, reducing post-harvest losses. Addressing foundational gaps in infrastructure and payments.	- AgriDigital (Zimbabwe/Zambia): Secured grain trading & instant payments for smallholders. - Twiga Foods (Kenya): Blockchain for food security & reducing losses in fresh produce supply chains. - FairChain (Ethiopia): Direct trade for coffee farmers, increasing incomes by ~40%.	Limited digital infrastructure, internet connectivity, and smartphone penetration in rural areas. High upfront costs for technology adoption.	Leveraging blockchain to leapfrog traditional banking and traceability barriers, directly connecting small-scale farmers to markets and finance.
Latin America	Export verification, premium market access, complying with international regulations (EU deforestation laws).	- Brazil: Blockchain for verifying deforestation-free beef and coffee exports. - Farmer Connect (Colombia): IBM-backed platform for consumer traceability of coffee, boosting producer revenues. - BeefChain (Argentina/Uruguay): Provenance tracking for premium grass-fed beef exports.	Navigating complex land ownership records, ensuring data input from remote farms, and aligning diverse stakeholders on a single platform.	Using blockchain as a competitive advantage to guarantee product quality and ethical standards for high-value export commodities, commanding premium prices.
Europe & North America	Consumer transparency, food safety compliance, brand protection, and optimizing complex supply chains.	- IBM Food Trust (Walmart, Carrefour): Traceability for produce & meat, reducing recall times from days to seconds. - EU Blockchain Observatory (Olive Oil): Combating counterfeit "Italian" olive oil. - Unilever (Palm Oil): Ensuring deforestation-free supply chains from Indonesia.	Stricter data privacy regulations (GDPR), high operational costs, and integrating with highly automated but legacy systems.	Enhancing brand trust and consumer confidence through unparalleled transparency, while improving logistics efficiency and compliance with stringent food safety standards.
Asia-Pacific	Combating food fraud, ensuring safety in complex supply chains, and accessing export markets.	- TE-FOOD (Vietnam): Farm-to-table traceability for pork and vegetables, preventing fake organic labels. - Thailand Jasmine Rice: QR codes for verifying authenticity and origin, reducing counterfeit exports. - Woolworths (Australia): Using blockchain for produce traceability back to individual farms.	Diverse and fragmented farming landscapes, prevalence of smallholders, and varying levels of government support and regulation.	Addressing widespread issues of food fraud and mislabeling specific to regional markets, thereby protecting domestic consumers and enabling premium export opportunities.

2. CRITICAL COMPONENTS OF BLOCKCHAIN FOR TRACEABILITY IN AGRI-SUPPLY CHAINS

2.1 Unique Digital Identifiers (Digital Twins)

The foundation of blockchain-enabled traceability in agricultural supply chains lies in the creation and management of unique digital identifiers that serve as immutable digital twins for physical products. These identifiers, typically implemented through QR codes, RFID tags, or cryptographic tokens, establish a one-to-one correspondence between a physical agricultural product and its digital representation on the blockchain. Each identifier contains a distinctive cryptographic signature that cannot be replicated or forged, ensuring the authenticity of the linked product throughout its journey from farm to consumer. The digital twin evolves dynamically as it moves through the supply chain, accumulating verified data points about its origin, handling conditions, processing stages, and transportation history. Advanced implementations (Bumblauskas et al., 2020) may incorporate biometric markers or DNA tags for high-value commodities, creating an even more robust connection between physical goods and their digital records. These digital twins serve as the anchor points for all subsequent blockchain transactions, enabling seamless tracking while preventing duplication or substitution of products. The system's effectiveness depends on the careful initialization of these identifiers at the point of origin, often involving secure generation protocols and multi-factor authentication to prevent counterfeit entries. By maintaining this persistent digital-physical linkage, the blockchain creates an auditable chain of custody that transforms supply chain transparency from an aspirational goal into an operational reality. Examples of using Unique Digital Identifiers (Digital Twins) in Agri-Supply Chains is shown in table 2.

Table 2: Examples of Unique Digital Identifiers (Digital Twins) in Agri-Supply Chains

S.No	Name of the Application	Explanation	Data Stored	Usage	Example
1	Farmer Connect - IBM	Each bag of coffee beans is tagged with a unique QR code linked to a blockchain record.	Farm location, harvest date, processing method, fair trade certifications, and roasting details	Buyers can scan the code to verify the coffee's origin and ethical sourcing claims.	"Thank My Farmer" initiative by Farmer Connect (backed by IBM) lets consumers trace coffee back to the exact farm in Colombia or Rwanda.
2	Wine Blockchain, Europe	Near-field communication (NFC) chips embedded in wine labels	Vineyard location, grape harvest date, fermentation process, and shipping conditions	Stops counterfeit "Italian" or "French" wines by verifying true origin.	BlockBar sells premium wines with NFC-linked blockchain certificates to prove authenticity
3	Walmart & IBM Food Trust	Blockchain-tracked barcodes on mango shipments	Farm location, picking date, cold storage logs, and customs clearance records.	Reduced traceability time from 7 days to 2.2 seconds.	Walmart mandates blockchain tracing for all leafy greens and tropical fruits.
4	TE-FOOD, Vietnam	Blockchain-based QR codes on organic vegetables	Soil quality tests, pesticide-free certifications, and transport humidity logs.	Buyers in supermarkets scan to confirm no synthetic chemicals were used	TE-FOOD tracks pork and veggies in Vietnam, preventing fake "organic" labels.
5	AgriDigital, Australia	Blockchain tokens linked to grain silos with DNA markers.	Moisture levels, protein content, and ownership transfers	DNA tagging prevents grain mixing or theft during storage	AgriDigital's platform handles 500,000+ tons of grain annually with blockchain IDs

2.2 Decentralized Data Verification

Unlike traditional supply chain systems where a single company or authority maintains centralized control over data, blockchain employs a distributed network architecture where information is replicated and synchronized across multiple nodes (computers) participating in the ecosystem (Pearson et al., 2019). In an agricultural supply chain context, these nodes typically represent different stakeholders - including farmers, cooperatives, processors, logistics providers, certifiers, and retailers - each maintaining an identical copy of the ledger. For instance, in a coffee supply chain blockchain, a farmer in Colombia might operate a node to record harvest data, an exporter's node would log shipping details, a roaster's node would document processing parameters, and a retailer's node would track final distribution, with all these entries being automatically propagated across the entire network. This decentralized approach eliminates single points of failure and prevents any one entity from unilaterally altering records, as changes only become valid when the majority of nodes reach consensus about their accuracy. The distributed nature also enhances system resilience - even if several nodes go offline, the network continues functioning with the remaining active participants, ensuring uninterrupted traceability from farm to consumer. Examples of using decentralized data verification is shown in table 3.

Table 3: Examples of using decentralized data verification in Agri-Supply Chain

S.No	Name of the Application	Problem	Solution given by Decentralized data verification	Outcome
1	European Olive Oil (Authenticity)	80% of "Italian" olive oil is fake or diluted	EU Blockchain Observatory created a system where: Italian farmers log harvests. Chemical labs test oil purity. Bottlers confirm no mixing.	Each step requires 3+ independent approvals before being locked on-chain
2	Fair Trade Coffee (Farmer Connect)	Farmers often lie about "fair wages" to get certifications.	Blockchain records payments where: Cooperatives verify farmer identities. Buyers confirm purchase prices. NGOs audit records	Brands like Starbucks can prove no child labor was used.

2.3 Smart Contract for Automated Compliance

In order to ensure compliance throughout agricultural supply chains, smart contracts self-executing digital agreements integrated within blockchain networks—automatically enforce predetermined rules and conditions. Without the need for middlemen, these contracts only take action when sensor data or stakeholder inputs satisfy predetermined standards. Examples of these actions include payments, quality checks, and penalties. A smart contract might, for example, stop shipments if contamination is found or release payment to a farmer upon IoT-confirmed delivery of (Behnke & Janssen, 2020) perishable goods within predetermined temperature thresholds. Smart contracts standardize adherence to food safety, ethical sourcing, and sustainability protocols, eliminate transaction delays, and reduce fraud by encoding compliance into tamper-proof blockchain records. Smart contracts improve trust, efficiency, and accountability while reducing human error or manipulation in real-world applications, such as AgriDigital's grain transactions or Walmart's cold-chain monitoring.

2.4 IoT & Sensor Integration in Agri-Supply Chains Based on Blockchain

By enabling real-time, tamper-proof monitoring of products from farm to fork, the combination of blockchain technology and Internet of Things (IoT) devices and sensors transforms agricultural supply chains (Kouhizadeh & Sarkis, 2018). An immutable audit trail is created when IoT sensors, like temperature, humidity, GPS, and soil condition trackers, automatically log vital data (like crop health, storage conditions, and transit conditions) onto the blockchain. For instance, soil moisture sensors confirm sustainable farming methods, and temperature sensors in strawberry shipments guarantee the integrity of the cold chain. By enabling stakeholders (farmers, distributors, retailers, and consumers) to confirm product authenticity and handling compliance via QR codes or mobile apps, this real-time data transparency improves food safety, lowers spoilage, and fights fraud. In conjunction with smart contracts.

3. SMART CONTRACTS FOR PAYMENTS & FARMER EMPOWERMENT

Blockchain-powered smart contracts are revolutionizing financial transactions in agricultural supply chains by automating payments, reducing delays, and (Feng et al., 2020), (Sander et al., 2018) ensuring fair compensation for farmers. These self-executing digital contracts trigger predefined actions when specific conditions are met—eliminating intermediaries, reducing fraud, and improving transparency. The way in which smart contract works in Agri-Payments is given below in the following steps which is shown in figure 2.

Step 1: Activate & Connect Sensor with App

The process starts when the producer affixes an IoT sensor (temperature/humidity) to product packaging and connects it to a mobile app. This allows to create a digital identity for a physical product on the blockchain.

Step 2: Sensor Recording During Transit

While in transit, the sensor continuously records, and logs environmental conditions (for example, 2-8 °C for perishables). The environment data is transmitted to the blockchain ledger in real-time via cellular/WiFi, creating a tamper-proof record.

Step 3: Transit Conditions Verified Instantly

At each moment while in transit (for example - warehouse, distribution centre), stakeholders are able to scan the package to immediately verify Temperature/humidity compliance, Geolocation movements, the chain of custody for the item at that moment.

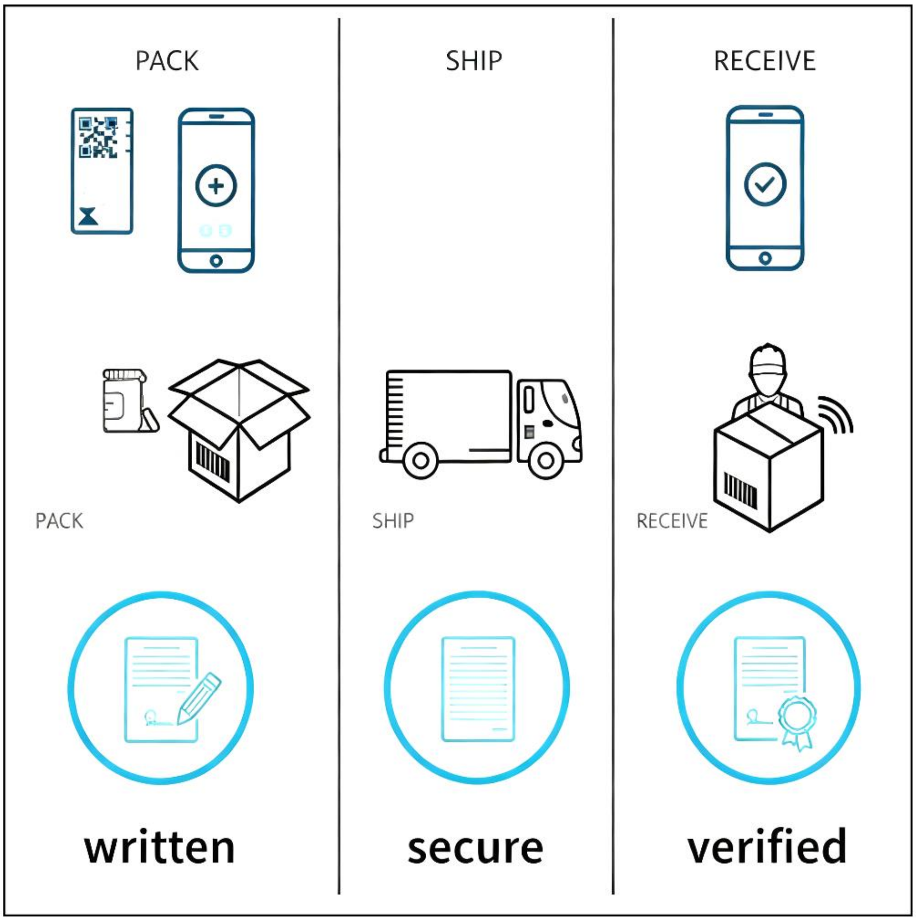

Fig 2: Smart Contract in Agriculture Supply Chain

Step 4: Blockchain Smart Contract Written (PACK Phase)

There would be an initial packaging phase and the quality parameters (For example, "max 4°C") would be encoded in an Ethereum smart contract and the payment terms (for example, 10% penalty for every °C variation) would be programmed.

Step 5: Blockchain Smart Contract Secured (SHIP Phase)

The contract is deployed on chain with the Farmer's wallet to receive payment, Purchaser's compliance requirements and IoT sensor identifier for automatic data feeds.

Step 6: Blockchain Smart Contract Verified (RECEIVE Phase)

At the point of delivery the blockchain would verify that all sensor log entries against the chain of custody in the contract and if everything is compliant: the farmer would automatically receive the smart contract payment in crypto to their wallet. If the product was not compliant on the delivery a payment would be held in escrow until the investigation was completed.

3.1 Advantage of Fraud Prevention and Food Safety

Blockchain technology is revolutionizing fraud prevention (Hald & Kinra, 2019), (Wang et al., 2019) and food safety in agriculture by creating an immutable, transparent, and tamper-proof record of every product's journey—from farm to fork. Unlike traditional paper-based or centralized digital systems, blockchain ensures that no single entity can manipulate data, making it a powerful tool against food fraud and contamination risks. Blockchain Enhances Fraud Prevention & Food Safety by providing solutions to the following problems which is shown in table 4.

Table 4: Use Cases of Fraud Prevention and Food Safety in Agri-Supply Chain

S.No	Use Case	Problem	Solution given by Blockchain	Real world example
1	Eliminating Food Fraud	Food fraud—such as mislabeling, adulteration, and counterfeit certifications—costs the global food industry $40 billion annually.	• Digitally certifying origins (e.g., verifying "Italian olive oil" truly comes from Italy). • Storing lab test results (e.g., proving honey isn't diluted with syrup). • Tracking ownership transfers (preventing "gray market" diversion of premium products).	European Olive Oil Fraud – Up to 80% of "Italian" olive oil is mislabeled. The EU Blockchain now tracks olive oil from grove to bottle, with chemical test results stored on-chain to prove authenticity
2	Rapid Contamination Tracking	When foodborne outbreaks occur (e.g., E. coli in lettuce), traditional traceability systems take days or weeks to identify the source	• Recording every handling step (farm, processor, distributor, retailer). • Automating recalls via smart contracts if contamination is detected	Walmart's Mango Traceability – Walmart, using IBM Food Trust, traced mango shipments from Mexico to US stores in 2.2 seconds (vs. 7 days previously). This prevents mass recalls by isolating contaminated batches.
3	Preventing Fake Organic & Fair Trade Labels	Fraudulent organic, non-GMO, and fair trade claims deceive consumers and hurt honest farmers	• Links certifications to real farm data (e.g., pesticide use logs). • Requires multi-party verification (farmers, inspectors, NGOs).	In Thailand, premium Jasmine Rice now carries QR codes that let consumers trace every grain back to its organic farm, with immutable records of soil tests, harvest dates, and shipping conditions, reducing counterfeit exports by 65% while boosting farmer incomes by 20%—proving how decentralized verification builds trust across the food chain.
3	Cold Chain Monitoring for Perishables	Just 2 hours in high humidity can trigger mold growth, leading to Aflatoxin contamination (a carcinogen)and 10B$ rise in annual global losses from spoiled grains.	Blockchain and IoT are safeguarding global food supplies—smart sensors now track temperature and humidity in real time during transit, with immutable blockchain records preventing spoilage while ensuring fair payments	In Nigeria, rice exporters reduced losses by 40% using this system, while USDA now accepts blockchain logs as legal proof of grain safety, demonstrating how technology can build resilience across agricultural supply chains.

3.2 Sustainability & Ethical Sourcing Through Blockchain in Agriculture

Blockchain technology is playing a transformative role in promoting sustainability and ethical sourcing across agricultural supply chains by providing verifiable, tamper-proof records of environmental and social compliance. Unlike traditional certification systems—which rely on paper trails and periodic audits that can be falsified—blockchain creates an immutable digital ledger that

tracks every stage of production, ensuring claims like "organic," "fair trade," or "deforestation-free" are backed by real data. The ways in which Blockchain Enhances Sustainability & Ethical Sourcing
3.2.1 Carbon Footprint Tracking

Blockchain records emissions data at each supply chain stage, from farm inputs (fertilizers, water usage) to transportation (fuel consumption). Example: The Carbon Trust and IBM partnered to create a blockchain system that tracks the carbon footprint of coffee beans, allowing brands to market low-emission products accurately.

3.2.2 Deforestation-Free Supply Chains

Palm oil, cocoa, and soy industries are notorious for illegal deforestation. Blockchain, combined with satellite imagery, verifies that farms comply with sustainability pledges. Example: Unilever uses blockchain to ensure its palm oil suppliers in Indonesia do not contribute to rainforest destruction.

3.2.3 Fair Wages & Labor Conditions

Smart contracts ensure farmers receive agreed-upon prices without middlemen undercutting payments.
Example: FairChain Foundation in Ethiopia uses blockchain to guarantee coffee farmers receive 40% higher wages by directly connecting them to global buyers.

3.2.4 Organic & Non-GMO Verification

Fraudulent "organic" labels cost the industry $40B annually. Blockchain tracks seed origins, pesticide use, and handling to prevent fraud. Example: TE-FOOD in Vietnam certifies organic vegetables by recording soil tests and harvest data on-chain.

4. INTEGRATION WITH INDUSTRY 6.0 TECHNOLOGIES

The convergence of blockchain, IoT (Internet of Things), and AI (Artificial Intelligence) under the Industry 6.0 framework is revolutionizing agricultural supply chains by enabling real-time quality monitoring, predictive analytics, and autonomous decision-making. This integration enhances traceability, efficiency, and sustainability, transforming traditional farming into a data-driven, smart ecosystem. A complete blockchain framework for agricultural supply chain management with IoT devices, smart contracts, and distributed databases that produce a transparent and automated channel from farm to table and is shown in figure 3. The framework consists of three integrated layers.

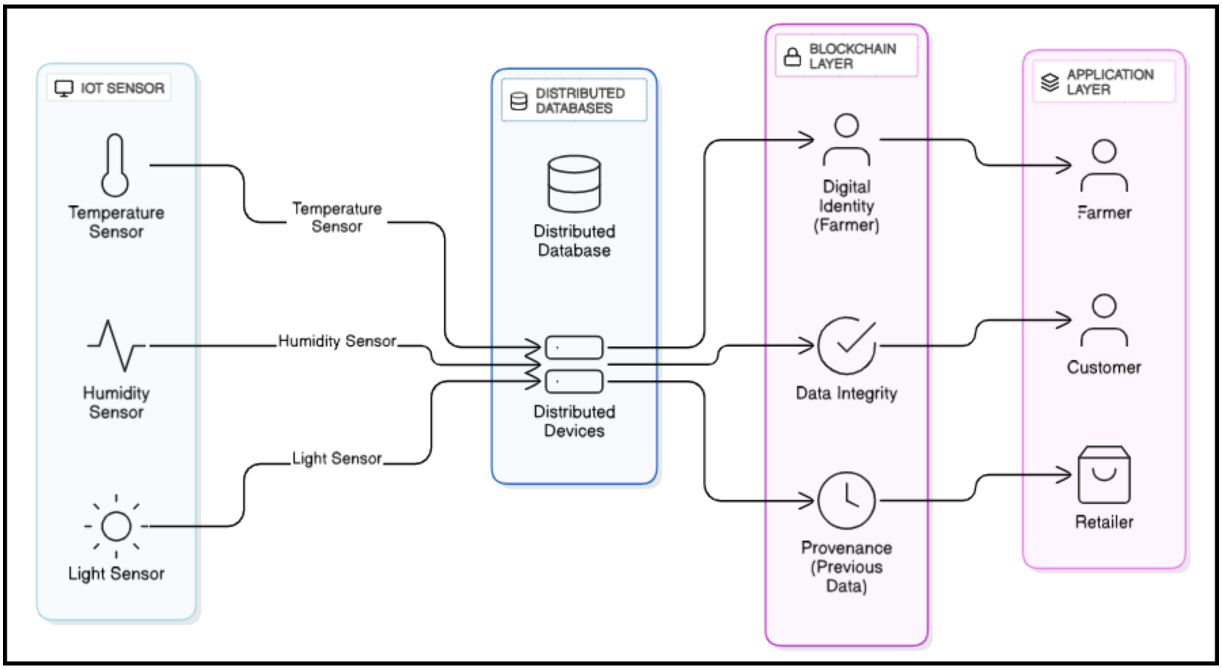

Fig 3: *Architecture of Agriculture Supply Chain*

4.1 Physical Layer: Real-World Data Collection

At the Physical Layer, the real-life realities of farming/ logistics now intersect with digital plant, product, and process monitoring. The Physical Layer consists of a web of Internet of Things (IoT) sensors and devices located right in agricultural fields, storage space, and transportation units to collect real-time data about agricultural products and their environment. For instance, GPS-enabled tracking devices can track a shipment's last leg of your shipment from farm-to-market, and the product itself can have a unique digital identifier using Radio Frequency Identification (RFID) tags and QR codes. Mobile phone apps connect farmers and this Physical Layer to account for the harvest from a crop when it is made manually by a farmer and a sensor built into the ground field, doing it automatically reminds the farmer, or sends an alert. For example, a coffee cooperative might have solar-powered soil sensors with the charge to transmit organic farming data to the IoT system, where it creates a link as the first link in an uninterrupted chain of custody. This physical-digital relationship generates raw agrifood and agricultural commodities with traceability properties and information for Blockchain verification.

4.2 Blockchain Layer: Trust and Automation Backbone

Smart contracts exist at the Blockchain Layer, following and executing rules without human intervention, for example automatically releasing payments once delivery conditions are met, or even enforcing penalties for breaking contract conditions. The Blockchain Layer provide three essential datasets: verified identities of all supply chain participants (so there is no chance of anonymous fraud), a complete product history (from the seed genetics to the supermarket shelf), and all the financial transactions made to each participant (which enables state-funded payments directly from farmers to buyers). Consensus mechanisms (such as Proof of Authority) validate new data blocks at the Blockchain Layer by balancing all transactions security with the speed required to track perishable goods. For example, when Australian grain trader AgriDigital records the shipment's weight and quality measurement at the IoT-enabled silo, this information is permanently and cryptographically sealed at multiple decentralized nodes, meaning that this information cannot be falsified and, at the same time, the farmer would receive an immediate payment.

4.3 Application Layer: Actionable Insights and Consumer Engagement

The Application Layer capitalizes on blockchain data to provide tools for different users in the supply chain. For example, farmers have access to mobile platforms that display real-time prices in the market, and at the same time allow for confirmation of payment without the delay of a bank. Food processors can see inbound shipments and use web dashboards to monitor compliance with safety thresholds. When food processors receive products, they may use AI algorithms to check for compliance with temperature records or storage conditions, and fluctuations from stated safety measures can be flagged. When the produce gets to retailers, they can engage consumers. Retailers may provide consumers with the ability to scan a simple QR code from the packaging of food that traces provenance in detail, including the location of the specific farm and attempts to communicate the sustainability of that farm in addition to its carbon footprint on the journey there. In some high-tech implementations, using machine learning, applications can analyze historical data encoded with a blockchain and provide predictive analytics to assess when would be an ideal time to plant crops, or to warn about anticipated-like disruptions in the supply chain.

5 SUSTAINABILITY AND ETHICAL SOURCING THROUGH BLOCKCHAIN IN AGRICULTURE

Blockchain technology is transforming sustainability and ethical sourcing in agriculture by creating an unalterable digital record of each product's path. Unlike paper certifications, which can be manipulated by fraud, blockchain provides unequivocal evidence that construction meets certain labor and environmental requirements at each step in the supply chain with its decentralized ledger. The technology records emissions from farm inputs such as fertilizers, through transportation fuel, and provides the exact amount of emissions per unit to establish level of effort. (Aung & Chang, 2014), (Kamble et al., 2020), (Queiroz et al., 2020) As noted by IBM and Carbon Trust in their collaboration tracing the environmental journey of coffee beans supplied from farm, it has the potential to track carbon footprint. Companies like Unilever are applying the same idea by verifying the rainforest destruction of their Indonesian suppliers with blockchain and satellite imagery, and logging it as evidence to hold suppliers accountable for the environmental impacts of commodities grown in areas of Deforestation and Environmental Impact (DEI). The transparency of the system can also ensure fair pay for farmers because it utilizes smart contracts to automatically enforce price pay, thus making the nemesis of those agreements, which is the unscrupulous middle-person, obsolete. The FairChain Foundation in Ethiopia successfully used blockchain to improve coffee growers' cash income by 40%, and the FairChain FAQ notes that "with Blockchain technology, the process from coffee farm to the consumer end user has become fully transparent, giving assurance that certifications of fair trade are being honored and that farmers are getting a fair price."

Another important use case is for addressing fake organic claims as blockchain provides proof of origin of farm practices with data from seed through sale. Vietnam's TE-FOOD system is an excellent example -- it records soil tests and harvest data on-chain to verify claims that vegetables are organic thus addressing an industry that loses $40 billion to phony certifications. By creating a seamless digital chain of custody from everything from water metric usage to documentation that fair wages are paid means there is now an auditable fact rather than wishy washy sustainability claims. The ability to verify through technology provides benefits to multiple stakeholders where growers are able to access premium markets on the back of verified claims and corporations can meet their ESG obligations backed by audit-able proof and where consumers can be assured that they purchase ethical and environmentally-certified products. As these applications demonstrate, blockchain takes agriculture sustainability from a marketing aspiration to an accountable reality, by making all claims.

By tackling important operational and financial issues in agricultural supply chains, blockchain technology shows a great deal of practical impact. Through blockchain-IoT integration, post-harvest losses—which cost developing economies about $310 billion a year (FAO, 2021)—have been decreased by 30–40% in initiatives like Nigeria's rice export programs. The EU's olive oil traceability initiatives and Thailand's Jasmine rice authentication demonstrate that blockchain-enabled systems can reduce food fraud, which accounts for an annual economic burden of $40–50 billion worldwide, by 50–65%. As evidenced by Walmart's traceability achievement of 2.2 seconds for mango supply chain verification, blockchain implementation also drastically improves recall efficiency from weeks to seconds while lowering traceability costs by 25–35% when compared to traditional manual systems (World Bank, 2023). These empirical findings support blockchain's ability to improve operational efficiency and verifiable sustainability claims while producing quantifiable socioeconomic benefits across agricultural supply chains.

Different regional trends in blockchain adoption for agricultural supply chains are revealed by international comparative analysis, highlighting both novel applications and contextual challenges. AgriDigital's operations in Zambia and Zimbabwe have reduced payment delays for smallholder farmers from 90 to 2 days, demonstrating how blockchain initiatives in Africa often address fundamental supply chain gaps and farmer empowerment. Meanwhile, Twiga Foods in Kenya uses blockchain to improve food security and reduce post-harvest losses, which are estimated to be between 30 and 40 percent in sub-Saharan Africa. In Latin America, implementations tend to concentrate on export-oriented traceability and premium market access. For instance, Colombia's Farmer Connect platform facilitates direct consumer-to-farmer transactions, increasing producer revenues by 20–25%, and Brazil's coffee and beef sectors use blockchain to confirm deforestation-free sourcing and comply with EU regulations. European applications, on the other hand, place a higher priority on fraud prevention, sustainability verification, and regulatory compliance. Two examples of this are Carrefour's blockchain-tracked free-range poultry, which boosted sales by 10% and strengthened consumer trust, and the EU Blockchain Observatory's olive oil traceability system, which cut down on fake "Italian" olive oil by 50%. These regional variations highlight how blockchain solutions are adapted to local infrastructure limitations, market demands, and economic priorities while also working together to create a more open, effective, and just global food system.

6 CHALLENGES & FUTURE TRENDS IN BLOCKCHAIN FOR AGRICULTURE

6.1. Scalability Issues in Blockchain for Agriculture

Blockchain technology holds immense potential for transforming agricultural supply chains, but its widespread adoption faces several critical challenges while simultaneously paving the way for innovative future trends. One of the most pressing issues is scalability, as current blockchain infrastructures struggle to handle the vast data volumes and transaction speeds required for global agricultural trade. Public blockchains like Ethereum can process only 15-30 transactions per second, far below the thousands needed for real-time tracking of perishable goods across continents [14], [15]. This limitation is compounded by the enormous data storage demands of continuous IoT sensor monitoring and the high energy consumption of proof-of-work consensus mechanisms, making many blockchain solutions environmentally unsustainable and cost-prohibitive for small-scale farmers.

6.2. Regulatory and Adoption Challenges

Regulatory uncertainty and adoption barriers present equally significant obstacles to implementation. The legal status of smart contracts remains ambiguous in most jurisdictions, leaving farmers without clear recourse if automated agreements fail. Divergent international standards for organic certification and food safety complicate cross-border blockchain tracking systems, while the digital divide excludes millions of smallholder farmers who lack smartphones or reliable internet access. Even when technology is available, misaligned incentives often stall adoption, as farmers bear the costs of IoT sensors and blockchain integration while retailers and consumers reap most benefits.

7 CONCLUSION AND FUTURE SCOPE

Using blockchain technology in agricultural supply chains is not only a technological advancement; it is a shift toward transparency, equity, and resilience in food systems around the world. This chapter has reviewed how blockchain is addressing some of the biggest problems in food production including food fraud, supply chain inadequacies, farmer exploitation, and environmental degradation, through the use of immutable record-keeping technology, smart contracts, and decentralized verification. We have seen how blockchain is equitable and transparent, from smart contracts to verify farm-to-fork traceability on Thailand's Jasmine rice crop, to ethical sourcing and purchasing of cocoa in Ghana, to real-world applications that not only help producers and consumers to build trust but also reward sustainable practices. Blockchain's merging with Internet of Things (IoT), artificial intelligence (AI), and decentralized finance (DeFi) creates possibility for Tokenized farm assets, AI-based predictive analytics, and automated climate insurance. As these technologies evolve and mature, blockchain could transform into an alternative to problem-oriented traceability solutions. It could actually provide the framework for a just and sustainable food economy: consumers making informed choices, farmers fairly compensated, and ecosystems sustained with verifiable stewardship.

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