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Blockchain-enabled agricultural supply chains for food security and sustainability: A systematic review

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Abstract

The global agricultural production system is a complex, multi-tier supply chain composed largely of smallholder farmers and plays a vital role in ensuring food security for a growing global population. However, traditional agricultural systems are characterized by inefficiencies, limited transparency, and information asymmetry, which contribute to trust deficits among stakeholders and increased food losses across the supply chain. Blockchain technology has emerged as a promising solution to address these challenges by enabling secure, transparent, and decentralized data management for all participants in agricultural supply chains. This article reviews the potential of blockchain as a governance mechanism in agriculture by examining key challenges such as traceability gaps, food fraud, post-harvest losses, and financial exclusion. It also provides an overview of core blockchain concepts and highlights selected real-world applications, including IBM Food Trust, AgUnity, BexT360, and Covantis. The findings indicate that blockchain can enhance traceability, facilitate equitable transactions between buyers and sellers through smart contracts, and support the creation of digital identities for farmers. However, challenges such as inadequate infrastructure, scalability limitations, and regulatory barriers remain significant. The integration of blockchain with complementary technologies such as the Internet of Things (IoT) and artificial intelligence (AI) can further improve sustainability, transparency, and food security, while promoting inclusive growth and strengthening the resilience of global agri-food systems.

Keywords: Blockchain; agricultural supply chains; food security; traceability; smart contracts; digital identity; IoT; sustainability; transparency; decentralized systems

1. Introduction

Production of food globally is carried out by a complex interrelated system of agricultural cycles occurring across multiple countries throughout our planet. This system plays an important role in the world economy by providing the ability for us to produce many crops as well as other products (meat, fish), which include all the things that can be produced from animal husbandry (dairy, eggs, wool, etc) with a large percentage coming from livestock breeding; ultimately contributing to the world's food supply. Unfortunately, while global food supplies are high, people continue to go hungry because of poor distribution chains, access issues, and poor use of food resources ^[1]. Agricultural Supply Chain(s) consist of a variety of stakeholders which include: Farmers, Intermediaries, Processors, Distributors & Retailers. This multi-tiered nature of the Agricultural Supply Chain also leads to fragmented, opaque and asymmetric forms of information between various participants within the Agricultural Supply Chain, resulting in a lack of confidence amongst participants, and ultimately leading to issues such as: pricing inequities, food counterfeit, logistical inefficiencies and coordinating supply chains ^[5]. Additionally, the agricultural supply chain is facing large amounts of food waste due to the loss of crops once harvested (post-harvest loss) – this is especially prevalent in developing countries due to a lack of appropriate infrastructure and ineffective handling practices

around harvested crops ^[3].

Traditional agricultural supply chain systems have been exposed by recent global interruptions, including COVID-19. Recent global shocks have emphasized a lack of real-time visibility and coordination in agricultural supply chains, which has led to breakdowns in agricultural supply chains as well as wasted food and reduced access to markets for farmers ^[2]. Therefore, there is an urgent need for more resilient, transparent and efficient systems that will assist in managing agricultural supply chains effectively. The technologies of Blockchain have clearly now begun to present themselves as a viable alternative to deal with these Structural Issues. The Blockchain technology is a Global, permanently recorded Digital Ledger which allows for safe and transparent Sharing of Data between multiple Stakeholders without having to rely on or go through a Central Authority ^[4]. The four key Benefits of Blockchain technology, Transparency, Immutability, Decentralisation and Programmability, would appear to make Blockchain Technology particularly well-suited for Enhancing Traceability, Accountability and Trust within agri-food systems ^[6].

Blockchain in Agriculture: Improving Supply Chain Efficiency and Supporting Food Security Through Increased Attention and Interest in Improving Supply Chain Efficiency and Supporting Food Security Through Use of Blockchain Technologies for Creating a More Efficient and

Secure Supply Chain. Benefits of Blockchain in Agriculture - Real-time Tracking of Agricultural Products and Automated Transactions Through Smart Contracts. Reduce Fraud, Increase Traceability and Improve Access to Markets for Smallholder Farmers ^[16]. Support Creation of Digital Identities and Transaction Records - Critical for Financial Inclusion and Access to Credit ^[9]. The goal of this review article is to study how blockchain technology can be utilized in the agricultural supply chain and provide information about how it affects the availability of food and the sustainability of production methods. The review will look at previous studies that have been conducted on the challenges facing agri-food supply chains such as traceability issues, food fraud, post-harvest loss and financial exclusion. It will identify current examples of the use of blockchain in agri-food systems and evaluate both the benefits and drawbacks of adopting the use of blockchain in the agri-food supply chain.

2. The State of Agricultural Supply Chains: Structural Challenges to Food Security

In order to recognize the capabilities of blockchain, we need to become familiar with the details of inefficiencies and the structure of traditional ag supply chain systems - no matter if they occur on a local, regional, or global level. These traditional ag supply chains utilize a step-by-step, multi-party type of system that increasingly removes the primary producer (the farmer) from the supply chain and subsequently create numerous risks and inefficiencies at every phase of the supply chain.

2.1 Information Asymmetry and the Trust Deficit

Asymmetric Information is one of the leading and most damaging problems in agricultural supply chains. The economist Akerlof's work on Asymmetric Information won him the Nobel Prize. It refers to when one party in a transaction has superior information compared to the other party in the transaction. As referred to in the previous sentence, there is often an asymmetric information dynamic that exists in many forms and directions simultaneously. However, the most damaging effect of asymmetric information is the inequitable position of producers.

Producers, particularly smallholder producers in developing countries, have an extremely limited amount of access to information regarding markets. Typically they do not have access to real-time pricing data for markets that are geographically distant; they do not have access to the specific quality requirements or specifications for the end buyer of their product; they do not have access to information on the consumer preferences that they may face when trying to sell their product; and, typically, the only short-term weather forecasts they may have access to are the forecasts that are provided to them from local weather stations and not from long-term satellite images.

Because of these factors, many producers are subject to exploitation from intermediaries who have superior information and bargaining power. As an example, small-scale producers may sell their agricultural product at the price offered to them by a trader that passes through the area and sell their product to the trader with little knowledge of what the trader will ultimately sell that same product for at the wholesale market or the location in proximity to their

farm location, as much as three to five times the price that the farmer sold it to the trader for.

On the other hand, buyers and sellers are no longer able to confirm whether the item they are purchasing has the characteristics advertised. As such, when you see labels such as "organic," "fair trade," "shade grown," or "sustainably sourced," you can't evaluate these for yourself as an end-user. The result of this dilemma is a classic "lemon market" problem ^[5]; there are high-quality (ethically produced, safe, nutritious) and low-quality (fraudulent, contaminated, or conventionally produced) products that the consumer does not have means to differentiate & differentiate between high and low-quality products, as they do so pay average prices across all products. This average price for an unknown quality product decreases the market for high-quality manufacturers and drives producers from the market, creating a spiral of low-quality, lack of trust, and diminished incentive for producers.

Cost effects within the scope of trust are considerable and measureable. For example, in 2013, the European horse meat scandal came to light, resulting in an estimated €300 million of beef products containing undeclared horse meat in different countries (some contain 100 percent undeclared horsemeat) being recalled and destroyed. Additionally, this situation demonstrated the weakness of the complicated & opaque supply chain and resulted in significant loss of consumer confidence and brand value due to a trust gap that was created ^[6]. Many reports of fraudulent organic certifications, mislabeled fish species, and tainted-spices since that time have proved this problem persists.

2.2 Post-Harvest Losses and Systemic Inefficiency

Post-harvest losses (PHL) typically represent between 20-50% of total production for selected crops (especially for fruits and vegetables and root crops) in developing countries ^[7]. They, however, are not solely related to poor storage infrastructure; they are inherently related to poor coordination and communication throughout the entire supply chain (through inadequate/inconsistent market incentives) and to poor information sharing/decision-making.

Take the example of a tomato's journey through the supply chain of a typical developing nation. When harvested/transported at peak ripeness, tomatoes are placed onto trucks without being monitored for temperature until they reach their destination; they are transported along poor roads; they are sold to multiple intermediaries (each of which takes time to aggregate their respective tomatoes prior to resale); and finally arrive at a market where an estimated 40% of the tomatoes are spoiling or overripe due to bruising or discoloration. Thus, any delays, improper handling, and lack of current information concerning retail demand will contribute to waste.

Four hindrances exacerbate the losses. Due to their lack of storage and need for cash, farmers sell immediately after harvest at low prices. Intermediaries have access to storage, which allows them to wait until prices improve before selling. In addition, depending on paper-based records and manual processes slows accuracy down and increases the risk of document fraud (falsified weight or grade certificates), and makes it nearly impossible to determine when and where in the chain the loss will occur. Without

granular data showing where, when and for what reasons loss occurred, projected interventions to prevent it will not be possible.

From a food security perspective, post-harvest loss is a reduction to food availability, but production inputs are unchanged (land, water, labour, fertilizer). Reducing PHL may be one of the most cost-effective and environmentally friendly ways to improve food security; however, it is underfunded and often overlooked.

2.3 The Smallholder Empowerment Gap

Smallholder farmers, defined as farmers who till less than 2 hectares of land, make up about one third of global food production and 70-80% of food production in Asia and sub-Saharan Africa.^[8] But they are stuck in a cycle of poverty, low yield, and vulnerability because they have been systemically excluded from accessing economic opportunities from institutions and services.

Smallholders lack access to formal banking services, of which about 1.7 billion adults lack access to banks worldwide, with a large proportion being rural smallholder farmers.^[9] Those who do not have a bank account are unable to save securely, receive an electronic payment and to establish a credit history. Without a credit history or the ability to provide collateral that can be verified, smallholders cannot get access to formal loans for the purchase of improved seeds, fertilizers, irrigation equipment, or storage technologies, and they must rely on informal lending institutions that charge them exorbitant interest rates, putting them in a continuous cycle of debt.

The challenges for smallholder farmers, however, are not exclusively related to their lack of access to banking services. They also do not possess a verifiable digital identity nor a track record of their production. They do not have any formal documentation to demonstrate their production volume, yield, quality metrics or transaction history associated with their product(s). Even if a smallholder is able to provide a consistent quantity and quality of production to a buyer, that buyer has no credible and immutable record of that smallholder's contribution that would allow him/her to negotiate better price/terms with other buyers. In essence, smallholder farmers are economically invisible.

Lack of verifiable data has negative repercussions on smallholder farmers; without verifiable data regarding their production and business-related transactions, smallholder farmers cannot access insurance products (e.g., weather-indexed crop insurance) designed to mitigate the impact of climate-related risks (e.g., drought, floods). Smallholders who lack verifiable identity and transaction records cannot participate in carbon credit markets or any other emerging payment-for-ecosystem-services mechanisms; cannot demonstrate compliance with food safety or sustainability standards required by buyers in premium markets; and remain excluded from the formal economy and the systems necessary for building resilience and escaping poverty.

2.4 The Four Pillars of Food Security Under Stress

The above-mentioned problems – opacity, inefficiency, inequity, and exclusion – are inherently linked and undermine all four pillars of food security defined by the Food and Agriculture Organization (FAO):

- **Availability** – post-harvest losses reduce the available supply of food; and supply-chain disruptions (such as during COVID-19) drastically reduce the availability of food even when production remains sufficient to meet demand.
- **Access** – smallholder farmers, marginalized groups, and other members of society with little or no access to secure sources of financing may not have the financial resources to buy food even if it is readily available; hence, smallholder farmers are unable to get fair prices for their products and are thereby unable to provide food for themselves during times of food scarcity.
- **Utilization** – without traceability of food products there is an increased risk of food fraud and food contamination; thus, consumers could receive food products that are not nutritionally sound and also produce safe consumption (e.g., contaminated fresh produce, adulterated spices, incorrectly labeled allergens) resulting in serious health problems and diminished nutritional outcomes.
- **Stability** – opaque, inefficient supply chains are brittle; therefore, there is no means of providing real-time visibility into how supply-chain disruptions will cause conflated effects (i.e., relative price spikes and local shortages) as a result of shocks (e.g., weather events, pandemics, and/or conflicts); therefore, the very foundation of conventional supply chains creates an environment that most excessively impacts the stability pillar of food security.

Using the backing of a society operating at a systemic failure, where the gap between rich and poor grows wider every day, and new and growing vulnerability both exist side by side in today's world – has contributed greatly to the interest in blockchain technology by research groups, agribusiness leaders, development organisations, and political decision makers.

3. Blockchain Technology Demystified: A Technical Foundation for Agricultural Applications

The term 'blockchain' has become an intimidating buzzword for many people working in agri science and agriculture because it is most commonly associated with speculative cryptocurrencies and the hype of Silicon Valley. In reality, blockchain is simple to understand, but can have a significant impact on the management of data (data governance) and coordinating the actions of multiple partners (multiparty coordination). I refer to it as a common digital record, which is not owned or controlled by any individual or entity, and has the added benefit that no one can subsequently change that record without detection.

3.1 Core Principles and Architecture

Understanding blockchain requires you to know the following four principles that are dependent on each other: decentralization, immutability, transparency, and programmability.

Distributed Ledger: In contrast to the typical database that is held on a single server and controlled by one entity (e.g. a bank's computer), a blockchain ledger consists of copies of itself across the entire network of computers associated with it (nodes). Every participating node (or at least every

authorized participant depending on the type of blockchain) has access to the complete ledger. When a new transaction takes place, it is sent out to every node (the transaction is sent out). Therefore, no single entity can exert control over the entire transaction and data cannot be tampered with because there is no central point of failure.

Immutability via hash functions: Data is entered into the blockchain system in what are called "blocks." Each block contains packets of transactions, the date/time at which it was created, and a hash (cryptographic) value of the previous block. A hash function is a formula that converts any data of any size into a fixed length value (the hash) that appears random (the hash). Importantly, if any factor is changed in the data (e.g. one letter or number), it dramatically alters the function and no longer links to the next block in the chain. In order for an outside party to modify a block of a blockchain without any evidence or trace, this party would need to recalculate the hash associated with that block and all other blocks that come after it on a majority of all nodes at the same time. This is a computationally impossible task for a well-established network, such as Bitcoin, having sufficient hashing power or strong consensus algorithms.

Consensus Algorithms: Since blockchains do not have a trusted third-party that can assure the validity of all transactions, they need to agree upon the validity of transactions and the current state of the ledger. This is accomplished with consensus algorithms. The most widely known consensus algorithm is the PoW algorithm used by Bitcoin, which allows miners to compete with each other by solving computationally intensive problems. The first successful miner gets to place the new block onto the chain and earns a reward. PoW has very high energy usage compared to the PoS consensus algorithm. In PoS, validators are chosen to create new blocks and earn rewards based upon their staked amounts of the cryptocurrency. For private use cases using permissioned blockchains (e.g., supply chain), alternative consensus algorithms such as PBFT or Raft are more commonly used and require far less energy.

Self-Executing Smart Contracts - Smart contracts operate on blockchains and automatically execute a transaction when the terms and conditions of that contract have been satisfied by both parties. With a smart contract, there is no need for a human intermediary or a trusted third party to execute the contract, because the smart contract code will automatically execute the contract when the applicable conditions are met. For example, if a buyer and seller have an agreement to purchase a particular amount of goods and the seller ships the goods via GPS/Wi-Fi tracking using IOT technology, the buyer can set up a smart contract that will automatically transfer money from his digital wallet to the seller's digital wallet when the goods have been received by the seller at a pre-designated location. The contract is executed by the code, not a financial institution.

3.2 Types of Blockchain: Public, Private, and Consortium

Recognizing various categories of blockchain builds enables you to assess the trade-offs associated with each to ascertain their use in a particular agricultural capacity based on their architectural characteristics. Public (Permissionless)

Blockchains: Public blockchains such as Bitcoin and Ethereum allow anybody to enter the network; anyone may join the network, have visibility into the ledger, generate transactions, and be part of a consensus (as determined by each of their specific consensus processes). Through their open nature, public blockchains offer the highest level of both transparency and decentralization; however, they are considerably slower than private blockchains when it comes to transaction finality rates, require much more energy for transaction cycles (proof-of-work systems), and lack sufficient privacy for its participants to protect sensitive data related to prices or volume in commercial agricultural supply chains from competitors.

Private (Permissioned) Blockchains: Private blockchains are generally established and maintained by a single business organization; consequently, that organization has ultimate authority to determine who is allowed to enter the network, who has visibility into the ledger, and who has authority to transact in the ledger. As a result, private blockchains are capable of processing transactions more rapidly, consuming much less energy, and providing much stronger confidentiality than both public and private blockchains. However, they likewise do not achieve the inherent goal of decentralized technologies. Therefore, private blockchains that have been built and deployed are essentially databases that are accessible to all users but with cryptographic audit trails; they are virtually identical to traditional-based databases that operate within an organization and the trust of a single central authority.

Cooperative Blockchains: This is a hybrid model, which has become the most common blockchain architecture for the agricultural supply chain. The governance of this type of blockchain is shared by a limited number of pre-appointed members (i.e., a combination of large agriculture corporations, farmers cooperative, a logistics company, and a retailer). The means of reaching consensus will be through a limited set of nodes controlled by the members listed above. This governance structure meets the need for confidence in data integrity (no single company controls the data) and supports data retention efficiency (which is typically much faster than that of public chains). In addition, the private nature of transactions is maintained by limiting visibility of those transactions to authorized parties. IBM Food Trust, described more thoroughly later in this paper has been successfully implemented as a cooperative blockchain running on top of Hyperledger Fabric.

3.3 Distinguishing Blockchain from Traditional Databases

Another area of misunderstanding for people is how blockchains differ from regular shared databases. These two kinds of databases are fundamentally different in how they work and why those differences matter. In a traditional shared database (e.g., within a supply chain using a cloud-based program), there is typically one central administrative entity who has the ability to change, remove, or overwrite data within the database. This creates issues of trust; each user has to trust that the administrator will act honestly, competently and without having their account hacked. In addition, there is a single point of failure.

In contrast, when using a blockchain (especially in a permissioned consortium model), there is no one participant

who possesses the unilateral authority to change the historical record. If someone attempts to change a record, all other participating nodes will immediately detect that attempt because it will create a break in the hash chain. Thus, while transactions can be corrected (with new transactions that would evidence the correction) and therefore create an audit trail, there is no ability to erase or rewrite transactions in the database without having consensus between the majority of participants on the action to be taken. The "immutable audit trail" of the blockchain is what sets it apart from traditional shared databases and what provides the fundamental basis for the possibility of using it as a shared source of truth by parties that do not trust each other.

4. Applications in Agriculture: From Farm to Fork and Beyond

The stated theoretical benefits associated with blockchain technology directly lead to the implementation of practical applications within the food/agricultural value chain. Based on an analysis of existing academic literature and industry related report data from (2018 – 2025) it is possible to identify three interrelated areas of primary functionality: (1). Improved traceability and food safety (2). Fair and efficient transaction processing via the use of smart contracts (3). Providing smallholder farmers with a digital identity/ access to financial resources.

4.1 Enhanced Traceability and Food Safety

Traceability is one of the most researched applications of blockchain technology for agriculture. Supply chain recordkeeping has typically been done using fragmented, paper-based systems, which hinders visibility and makes it difficult to track where food comes from or travels to throughout the supply chain. By creating an immutable, time-stamped, shared ledger that can be accessed by all authorized participants, Blockchain technology can solve these issues ^[6].

Research has shown that using a blockchain system for traceability greatly improves the efficiency and accuracy of tracing food products. As an example, a blockchain-enabled platform can identify the origin of contaminated food products almost instantly versus using traditional methods

which can take days ^[17]. This is particularly useful in reducing the risk associated with food safety, as it helps to quickly identify contaminated food products and reduce the size of food product recalls. The use of IoT devices in conjunction with blockchain has also been cited as another important innovation to provide assurance of data reliability and real-time tracking. As IoT sensors gather data on environmental conditions such as temperature, humidity and location throughout transport and storage, this information will be stored on the blockchain ^[18]. This provides greater transparency and helps to improve that food quality requirements are maintained through the supply chain. Even with the advantages described above, data entry points still present a challenge due to the lack of reliability (the "oracle problem") associated with third-party data sources. Blockchain networks depend on external data sources for information that could be polluted or manipulated.

In Case Study 2 BexT₃₆₀ has implemented its technology platform based on blockchain to allow the traceability of the production chain for products like coffee, cocoa, and seafood through the use of the Internet of Things (IoT) enabled coffee cherry sorting machines supported by computer vision that evaluate the size, colour and quality of coffee cherries at the time they are harvested from the smallholder coffee producer. The evaluation of each cherry is integrated into the blockchain with an associated digital identity of the producer, a geolocation and a timestamp. A smart contract calculates how much money will be sent using mobile money to the producer's digital wallet based on the cherry's grade and market price, with payment delivered immediately.

For the coffee buyer, BexT₃₆₀ provides an immutable provenance record from the point of origin to the roaster supporting premium pricing for verified premium or sustainably grown beans and for the producer, a transparent and immediate payment process that is based on an objective assessment of the producer's quality, thereby preventing the intermediary from underpaying or misrepresenting the grade of coffee cherries. Pilot projects conducted in Uganda and Colombia have demonstrated that producers experienced significant growth in income and a reduction in the time taken to receive payment. ^[11]

Platform	Primary Function	Technology Used	Key Benefit	Region/Use Case
IBM Food Trust	Food traceability	Hyperledger Fabric	Rapid product tracing (seconds vs days)	Global retailers (e.g walnuts)
Agunity	Farmer digital identity & transactions	Mobile + Blockchain	Financial inclusion & transparency	Papua New Guinea
BexT ₃₆₀	Commodity traceability (coffee, cocoa)	IoT + AI + Blockchain	Quality-based pricing & instant payment	Africa, South America
Covantis	Trade digitization (grains)	Blockchain consortium	Reduced paperwork and transaction delays	Global commodity trade

4.2 Fair and Efficient Transactions via Smart Contracts

The use of blockchain technology has been growing in popularity due to its ability to increase the efficiency of agriculture's supply chains. A key area of research into this subject relates to the use of smart contracts, which are automatically enforced contractual agreements that can operate without intermediaries, or middlemen. According to ^[16], implementation of smart contracts leads to lower transaction costs, faster execution (due to the removal of human handling), and greater trust among supply chain

partners. In an agricultural context, using smart contracts to automate payment to farmers upon verification of delivery conditions increases liquidity for the farmer and can decrease discrepancies regarding price or quality.

Another benefit of blockchain technology is that it streamlines the way that documentation is handled by creating a digital, verifiable record instead of using paper. By having electronic records, the amount of paperwork needed to be processed is reduced, resulting in less work for administrators, more accurate records, and improved

coordination between different parties. Research on various blockchain-based trade platforms has demonstrated that they also provide benefits in terms of improving the efficiency and speed of cross-border transactions by simplifying the problems associated with managing documentation and verifying information.

The scalability of agricultural supply chains presents another major concern for most agricultural systems. Given that agricultural supply chains generate such large amounts of data, many current blockchain systems may not have sufficient capacity to accommodate the significantly higher volumes of transactions that will be created by future agricultural supply chains. Additionally, the lack of standards across various blockchain systems creates further obstacles to achieving interoperability between different blockchain systems.

4.3 Empowering Smallholder Farmers Through Digital Identity

There is considerable evidence throughout the literature for the capability of blockchain technology to improve financial inclusion for small scale farmers. Farmers in many developing areas do not have access to formal financial services due to a lack of verifiable credit histories and reliable transaction records. By using systems based on blockchain, it can provide both digital identities (or "identifiers") and secure transaction logs (or "transaction records"), which can be used as the foundation to establish creditworthiness^[9]. Financial institutions will have access to an accurate, secure way of evaluating risks and can lend money as well as offer insurance and other forms of financial support.

AgUnity and BexT₃₆₀ are examples of how Blockchain technology can be put into productive use. Direct payment from farmers, eliminating intermediaries to provide direct payments, and ensuring transparent pricing are all ways in which Blockchain supports farmer empowerment with respect to transaction control and increased bargaining power. While there is significant potential for Blockchain to reduce the barriers that farmers face in accessing markets, some factors impede widespread adoption. The most significant impediments to Blockchain adoption include low digital literacy levels, poor infrastructure, and high initial implementation costs. To support inclusive access to Blockchain-based solutions, targeted policy interventions and the design of user-friendly systems must be implemented.

4.4 Reducing Food Waste Through Granular Visibility

Food security has multiple dimensions, which include availability, access, utilization, and stability. Blockchain supports increasing food availability by improving supply chain coordination and reducing post-harvest losses^[3]. Additionally, increased transparency and traceability will ensure that food is safe for consumption, which supports efficient utilization.

Through blockchain's ability to create market efficiencies and fair pricing mechanisms, farmers' incomes and purchasing power are increased, thereby improving their accessibility to food. Further, by enabling better risk management and providing real-time visibility on supply chain activities, blockchain enhances food stability and

reduces the effects of Business or Economic Interruption due to a pandemic or climate change. Blockchain helps with sustainability because it provides access to data regarding how agriculture was produced. There are also some negative concerns about how blockchain affects the environment, especially with energy use relative to consensus models used by some blockchains. In response, researchers are focusing on how permissioned blockchains can be a more energy-efficient alternative in the agricultural industry.

4.5 Research Gaps and Future Directions

There are many exciting possibilities for blockchain to revolutionise agricultural supply chains, but there are still many areas where we need to do more research. There is a large amount of literature that is confined to pilot studies or theoretical analyses of the use of blockchain technology in agriculture, but we are lacking in large-scale empirical validation of this emerging technology. And, while some of the technical roadblocks (e.g., scalability, interoperability, data integration) have been identified, they need additional investigation.

There is additionally very little research done on the impact of the socio-economic aspects of adopting blockchain in agriculture, especially as it relates specifically to developing countries where the digital divide may pose a barrier to the adoption of this technology. Governance issues regarding data ownership and regulatory issues surrounding the use of blockchain technology also require much more research. Future studies should aim to create scalable and inclusive blockchain technology, including the integration of blockchain technology with other technologies like IoT and AI, and developing common standards in order to encourage more widespread use of blockchain technology. Policymakers as well as all relevant participants need cooperative efforts to ensure that blockchain implementation contributes to equitable and sustainable farm development.

"Real-world implementations such as IBM Food Trust, AgUnity, BexT₃₆₀, and Covantis further validate the practical applicability of blockchain in improving traceability, financial inclusion, and supply chain efficiency."

5. A Critical Analysis: Barriers, Challenges, and Unresolved Questions

Although ample data from many pilot programs support the case for a much wider application of blockchain technology in agriculture, there are numerous significant barriers to achieving this goal. As an academic graduate student who believes in evidence-based research as a standard methodology, I will be providing a balanced perspective on the challenges that exist. Enthusiasm for the theory of how a technology will work is not a substitute for critical thought with regard to the actual application or actual science behind that theory.

5.1 Infrastructure and the Digital Divide

The primary and most important challenge preventing blockchain systems from being wholly beneficial exist in many areas of our world. The lack of basic digital infrastructures where it is expected to have maximum effect is an additional consideration. Blockchain systems,

including the least intensive systems (typically permissioned systems), require reliable internet connection capabilities; minimal use of short-range devices (e.g., smartphones/computers), access to sufficient electricity supply, and sufficient basic digital literate users.

Due to the lack of prerequisites in rural regions of sub-Saharan Africa and some areas of South Asia, it can be difficult to achieve the necessary standards for achieving internet connections. Specific statistics from the International Telecommunication Union (ITU) show that only 22% of households in sub-Saharan Africa have Internet access at home; rural connectivity is much less developed than in urban areas, (14) there are also many rural areas where electricity availability is inconsistent. There is high penetration of mobile devices even among poor countries; however, they are predominantly feature phones (non – smartphone).

Consumers have a difficult time accessing affordable data packages and will usually end up with higher bills for mobile services than connected Internet service providers would pay.

The risk of blockchain technology creating inequality in agriculture is significant. The first beneficiaries of these blockchain-based solutions will likely be large, high-volume farms in developed countries or in well-connected areas of developing countries. Therefore, smallholders will likely continue to fall behind while the large, high-volume farmers will grow even larger and more powerful. These inequities will only intensify the inequities present in the agricultural system. Any thoughtful discussion of using blockchain to improve food security must include this potential for creating inequitable outcomes and must place a great deal of emphasis on designing solutions that are equitable.

5.2 Scalability and Throughput Limitations

Several of the existing blockchain architectures cannot adequately process or maintain the staggering volume of transactions generated in a global food supply chain. A single shipment of fresh produce generates over 1,000 different data elements about itself for the complete journey—from field to consumer. This includes the temperature at which it was stored, location (GPS coordinates), the number of inspections it passed, weight, customs documentation, payment received, etc. Also, no current technology is available that will allow these systems to scale to millions of users while processing billions of transactions per day across many global supply chains.

The Ethereum blockchain is the largest public platform for executing smart contracts and is capable of processing between 15 and 30 transactions per second (tps). In comparison, Visa averages about 1,700 tps and can peak around 24,000; Hyperledger Fabric can process over 3,500 tps with greater efficiency through more effective consensus mechanisms when using a permissioned blockchain. Both systems face similar growth challenges from the number of users and data associated with them^[15].

Without interoperability (the ability of multiple blockchain networks to transfer and share information across different platforms), we risk creating new separate data silos that can be as or more problematic than the previous separate data silos. For example: if a farmer is on AgUnity; if a logistics provider is on TradeLens; and if a retailer is on IBM Food

Trust - none of whom can send or receive verified, accurate data from each other, they will be disconnected in the chain of custody. There are currently active projects looking into cross-chain interoperability, but cross-chain interoperability has not been sustained at this time.

5.3 Energy Consumption and Environmental Footprint

There have been a lot of concerns over how much energy Proof-of-Work (PoW) public blockchains (e.g., bitcoin) consume in total. Bitcoin mining alone uses approximately 110 to 150 terawatt hours (Twh) of electricity annually. This amount of energy is similar to the total annual electricity consumption of all of Argentina. As such, PoW mining cannot be considered to be environmentally sustainable and therefore cannot support any climate-focused agricultural initiatives. It is important to note, however, that PoW's energy consumption cannot necessarily be viewed as an inherent characteristic of the blockchain technology itself; rather, it is caused by the consensus mechanism (PoW) unique to these types of public blockchains.

While it is clear that PoW public blockchain solutions (such as Bitcoin and Ethereum) should be evaluated negatively with respect to climate change because of their high levels of energy consumption, this does not mean that all blockchain technologies can be considered "bad for the environment." In contrast, today's typical use of permissioned (or consortium) blockchains for building agricultural supply chains uses very different forms of consensus (from PoW) and consumes only a fraction of the energy consumed by PoWs; for instance, Hyperledger Fabric consumes approximately the same amount of energy as a typical distributed server system. Thus, although the environmental argument against using blockchain technology in agriculture is valid when considering PoW public blockchains, it is largely invalid when considered with respect to consortium blockchains being used within supply chains. Nevertheless, there continues to be a large amount of public uncertainty regarding this situation which poses a serious risk of reputation damage.

5.4 Data Quality and the Oracle Problem

Data stored on a blockchain cannot subsequently alter, but that fact does not guarantee that the stored data is accurate. This problem, known as the "oracle problem" or "garbage-in, garbage-out" problem cannot ensure that a farmer's organic certificate submitted, or the readings from an atmospheric sensor that has a malfunctioning issue, would not get recorded indefinitely on the blockchain. To develop a solution for the oracle problem correctly, developers need to pay careful attention to the design of their applications. The applications can make use of trusted oracles (i.e., third-party services that will verify and authenticate off-chain data before submitting to the blockchain) and utilize IoT devices or automated systems to reduce or eliminate the need for humans to enter data. Additionally, economic incentives can be provided to the owner of the data to ensure that the data is reported accurately rather than inaccurately. However, in every method listed above, the risk of submitting inaccurate data must be accounted for in order to assure that the record of trust has moved from the integrity of data (can I trust that the record has not been altered) to the veracity of data (can I trust that the record reflects what

happened in the real world).

5.5 Governance, Standards, and Regulatory Uncertainty

A successful supply chain blockchain requires establishing formal governing rules that determine the rules and accountability of the blockchain. This includes determining who can participate in the supply chain blockchain, defining the data standards for blockchain, and determining how disputes will be resolved over Recorded Transactions. Establishing these basic governing rules is done in various ways depending on where you are and how you implement your Supply Chain Blockchain. Each location can implement different methods for establishing their governing rules. Individuals may also implement their Supply Chain Blockchain differently than other individuals. The lack of a clear understanding of legality is also a significant barrier to the establishment of supply chain blockchains at this time (i.e., are smart contracts enforceable in a court of law?). Additionally, how do data privacy and security laws (like GDPR) impact the ability to have an immutable blockchain? If there is no way to delete information from a blockchain, how can an individual exercise their right to delete personal data? These questions and other related issues must be resolved before supply chain blockchains can be established.

6. The Path Forward: Enabling Conditions and a Holistic Approach

Blockchain can enhance global food security; however, it is not a silver bullet for all issues related to food security. Rather than being an all-encompassing solution to the challenges of food security, the effectiveness of using blockchain to address food security will depend upon the degree of incentives, governance, and networks of complementary technology that surround the use of this tool. Therefore, when implementing blockchain in a way that enhances food security, you must do so holistically and consider each element of the food system.

6.1 Designing for Inclusion from the Ground Up

When developing blockchain solutions for smallholder farmers as the primary stakeholder, it's important to design a low-cost, low-tech user interface that can function without an internet connection. For example, if a farmer has only a basic feature phone, they would need to use a USSD (text-based) code to log their harvest and receive a corresponding verifiable token representing that harvest, which will then be uploaded to the blockchain once an internet connection is usable. The goal of the blockchain solution must be to help farmers address specific or immediate issues such as establishing provenance so that farmers can access premium markets, receive prompt, transparent payment, or establish verifiable transaction history for loans—not simply because it is technically feasible to do so.

6.2 Collaborative Governance and Multi-Stakeholder Models

The most effective type of governance for future projects will be consortium blockchains that enable all the different parties (farming organizations, agribusinesses, transportation/logistics companies, retailers, possibly regulators and civil society) to have a real voice in their

governance decisions. This is much better than a fully public blockchain model or a top-down corporate-controlled governance model. Additionally, clear protocols governing data ownership, data validation, dispute resolution, and rights of participation need to be established before development begins, and be hard-coded into the smart contract logic. Finally, it should be made clear that governance is an ongoing process, and not simply a design decision made at some point at the beginning of a project.

7. Conclusion

The review demonstrates how blockchain technology has the potential to reshape the agricultural supply chain by addressing systemic inefficiencies at every level. By facilitating transparency, traceability, and decentralization, blockchain enhances confidence among all stakeholders and has the ability to increase food safety. In addition, smart contracts allow for fair and efficient transactions while digital identity systems enable smallholder farmers to improve their access to financial services and markets. Major collaborations, such as those between IBM Food Trust and AgUnity, BexT360, and Covantis, have implemented these technologies successfully in many agricultural contexts.

Even with these benefits, there are still significant problems, including subpar digital infrastructure, limited scalability, unreliable data, and questions about compliance with regulations. These limitations underscore the need for strong governance systems and common protocols to facilitate successful implementation. In addition, blockchain should not be viewed as a “stand-alone” solution; it needs to integrate into a larger digital ecosystem that includes complementary technologies such as IoT (Internet of Things) and AI (artificial intelligence).

To sum up, blockchain can offer great opportunities for creating more transparent, efficient and resilient agricultural and food systems. Success will require inclusive design strategies, collaboration among many parties and continued investments in digital infrastructure to provide equitable benefits for all actors across the agri-food value chain.

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