Jurnal Galaksi (Global Knowledge, Artificial Inteligent and Information System) E-ISSN: 3048-2399
Vol 1, No 3, December 2024 , pp.178-189
https://doi.org/10.70103/galaksi.v1i3.46

Blockchain Technology: A Review Study on Improving Efficiency and Transparency in Agricultural Supply Chains

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ARTICLE INFO

Article history:
Received 13 December 2024
Revised 26 December 2024
Accepted 29 December 2024
Available Online 31 December 2024

Keywords *:*
Agriculture;
Blockchain;
Economic Development;
Sub-Saharan Africa;
Supply Chain;

ABSTRACT

The agricultural sector is vital to economic development and food security in Sub-Saharan Africa (SSA). However, persistent challenges in agricultural supply chains, such as inefficiencies, lack of transparency, and limited traceability, contribute to high post-harvest losses, unfair pricing for farmers, and reduced consumer trust. Blockchain technology, with its decentralized and transparent ledger system, offers a promising solution to these issues. This review explores blockchain's potential to improve supply chain efficiency and transparency in SSA. By integrating blockchain with smart contracts, IoT devices, and real-time data sharing, stakeholders can enhance traceability, automate processes, and reduce transaction costs. Blockchain-based platforms provide direct market access for farmers, ensuring fair pricing and minimizing intermediary influence. Furthermore, blockchain's immutable nature guarantees data credibility, fostering consumer trust and compliance with quality standards. Despite its potential, blockchain adoption in SSA faces challenges, including high costs, inadequate infrastructure, limited technical expertise, and low awareness of its benefits. Addressing these barriers requires affordable, scalable solutions and supportive policy frameworks. This review highlights blockchain's transformative role in resolving inefficiencies and improving transparency in SSA's agricultural supply chains. Collaborative efforts among governments, private stakeholders, and international organizations are crucial to fostering adoption, driving economic growth, and enhancing food security.

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1. Introduction

Agricultural supply chains play a pivotal role in the economies and livelihoods of Sub-Saharan Africa (SSA), where over 60% of the population relies on agriculture as a primary source of income (Mavilia and Pisani 2022). These supply chains encompass a complex network of activities, including production, processing, storage, transportation, and marketing, all of which are integral to ensuring food security and driving economic growth. However, SSA's agricultural supply chains are

characterized by significant challenges that hinder their effectiveness and limit their potential to contribute to poverty reduction and rural development. One of the most pressing challenges is inefficiency (Bikoro 2022; Smidt and Jokonya 2022). Fragmented supply chains, compounded by inadequate infrastructure and unreliable logistics, lead to high transaction costs and post-harvest losses, which are estimated to range between 20-40% for perishable goods. Additionally, the lack of access to real-time market data further exacerbates inefficiencies, leaving farmers unable to make informed decisions about production and sales (Lee et al. 2022). Transparency is another critical issue, as the lack of visibility into supply chain operations fosters mistrust among stakeholders and enables fraudulent practices, such as misrepresentation of product quality and manipulation of pricing. Traceability issues also pose a significant barrier, particularly in export markets where stringent quality standards are required. The inability to track produce origins undermines food safety and reduces consumer confidence in agricultural products from SSA.

Blockchain technology offers a transformative solution to address the inefficiencies, transparency gaps, and traceability issues plaguing SSA's agricultural supply chains. At its core, blockchain is a decentralized digital ledger that records transactions across multiple nodes in a secure, transparent, and immutable manner (Yogarajan et al. 2023). This means that no single entity has control over the system, and once data is recorded, it cannot be altered or deleted. Key principles of blockchain include decentralization, which eliminates the reliance on centralized authorities; immutability, ensuring data integrity and trust; and smart contracts, which are self-executing agreements that automate processes based on predefined conditions.

Globally, blockchain has demonstrated its potential to revolutionize industries such as finance, healthcare, and logistics. In the agricultural sector, its applications are equally transformative. Blockchain enhances supply chain efficiency by automating transactions, reducing reliance on intermediaries, and enabling real-time data sharing among stakeholders. Transparency is significantly improved, as the immutable nature of blockchain creates a trustworthy record of all supply chain activities, fostering accountability and reducing fraud (Cao et al. 2022). Moreover, blockchain ensures robust traceability, allowing stakeholders to track agricultural produce from farm to table. This capability is especially critical for meeting export market requirements and addressing consumer concerns about food safety and quality. In the context of SSA, blockchain holds immense promise. It can address region-specific challenges such as unreliable market data, limited access to credit, and fraudulent certifications (Ronaghi 2021). By creating a transparent and efficient system, blockchain has the potential to empower smallholder farmers, enhance market access, and build trust among stakeholders across the supply chain.

This study seeks to explore the role of blockchain technology in improving the efficiency and transparency of agricultural supply chains in SSA. It aims to provide a comprehensive review of how blockchain can mitigate existing challenges, such as inefficiencies in logistics and resource allocation, lack of trust among stakeholders, and limited traceability of agricultural products (Kamble, Gunasekaran, and Sharma 2020). By examining the current state of blockchain adoption in SSA and highlighting successful use cases, the study intends to demonstrate the practical benefits and transformative potential of this technology for the region.

Additionally, the study aims to identify gaps and challenges in the adoption of blockchain technology in SSA's agricultural sector. Barriers such as high implementation costs, inadequate infrastructure, lack of technical expertise, and social resistance to change will be analyzed in detail. The study also seeks to provide insights into future research directions, emphasizing the need for affordable, scalable blockchain solutions, integration with other emerging technologies like IoT and AI, and the development of supportive policy frameworks (Ronaghi 2021). Ultimately, the study endeavors to contribute to the growing body of knowledge on blockchain technology and its application in addressing critical issues in SSA's agricultural supply chains.

2. Literature Review

Overview of Blockchain Technology in Agricultural Supply Chains

Blockchain technology in agricultural supply chains has gained significant attention in recent years. This literature review aims to provide an overview of the current state of blockchain technology in agricultural supply chains. A systematic review of academic literature published between 2017 and 2022 will be conducted using keywords such as "blockchain," "agricultural supply chain," and "food safety." The review will highlight the potential benefits of blockchain technology in agricultural supply chains, including improved transparency, traceability, and food safety (Martinez, 2022). Challenges and limitations, such as scalability, interoperability, and regulatory frameworks, will also be discussed. The review will conclude that blockchain technology has the potential to transform agricultural supply chains, but further research and development are needed to address the challenges and limitations.

Blockchain-Based Traceability Systems in Agriculture

Blockchain-based traceability systems have been increasingly adopted in agriculture to improve food safety and transparency. This literature review examines the current applications and future directions of blockchain-based traceability systems in agriculture. A comprehensive review of academic literature published between 2018 and 2022 will be conducted using keywords such as "blockchain," "traceability," "agriculture," and "food safety." The review will highlight the benefits of blockchain-based traceability systems in agriculture, including improved food safety, reduced counterfeiting, and enhanced consumer trust. Challenges and limitations, such as data management, scalability, and interoperability, will also be discussed. The review will conclude that blockchain-based traceability systems have the potential to improve food safety and transparency in agricultural supply chains, but further research and development are needed to address the challenges and limitations.

The Impact of Blockchain Technology on Agricultural Supply Chain Efficiency

The impact of blockchain technology on agricultural supply chain efficiency has been a topic of increasing interest in recent years. This literature review examines the current research on the impact of blockchain technology on agricultural supply chain efficiency. A systematic review of academic literature published between 2019 and 2022 will be conducted using keywords such as "blockchain," "agricultural supply chain," "efficiency," and "productivity." The review will highlight the benefits of blockchain technology in improving agricultural supply chain efficiency, including reduced transaction costs, improved inventory management, and enhanced supply chain visibility. Challenges and limitations, such as scalability, interoperability, and regulatory frameworks, will also be discussed. The review will conclude that blockchain technology has the potential to improve agricultural supply chain efficiency, but further research and development are needed to address the challenges and limitations.

3. Research Methods

The methodology for this study is cantered on a comprehensive review of existing literature to understand the application and impact of blockchain technology on agricultural supply chains in Sub-Saharan Africa (SSA). The literature review process involved the systematic selection and analysis of academic articles, industry reports, case studies, and policy documents. Selection criteria included relevance to blockchain applications in agriculture, geographical focus on SSA (Lee et al. 2022), and publication within the last decade to ensure the inclusion of recent advancements and findings. Studies were prioritized if they provided empirical data, case-specific examples, or a detailed discussion of challenges and opportunities in SSA's agricultural sector.

A diverse range of databases and sources were utilized to ensure the review covered a broad spectrum of perspectives. These included academic databases such as Scopus, Web of Science, and PubMed for peer-reviewed articles, as well as industry-focused platforms like IEEE Xplore and SpringerLink for insights into technological advancements. Reports from international organizations

like the Food and Agriculture Organization (FAO), World Bank, and African Development Bank were incorporated to provide a policy-oriented perspective. Additionally, grey literature, including white papers, conference proceedings, and relevant government documents, was reviewed to capture non-academic contributions to the discourse.

Analytical Framework

To evaluate the impact of blockchain technology on SSA's agricultural supply chains, an analytical framework was developed based on key criteria aligned with the challenges identified in the region. These criteria included:

Table 1. Analytical Framework for Blockchain Impact in SSA Agricultural Supply Chains

Criteria	Description
Cost Reduction	Assessment of how blockchain streamlines processes, reduces transaction costs, and minimizes financial inefficiencies in supply chains
Fraud Prevention	Analysis of the role of blockchain in ensuring data integrity, reducing fraudulent activities, and fostering trust among stakeholders
Traceability	Evaluation of blockchain's ability to provide end-to-end visibility of agricultural products, ensuring compliance with food safety standards and improving consumer confidence
Efficiency Enhancement	Examination of blockchain's impact on streamlining operations, automating processes through smart contracts, and reducing delays in supply chain activities
Stakeholder Inclusion	Investigation into how blockchain enables equitable participation of smallholder farmers, increases their market access, and ensures fair pricing

4. Results and Discussions

4.1. Agricultural Supply Chain Challenges

Inefficiencies in Processes

The agricultural supply chains in Sub-Saharan Africa (SSA) are plagued by significant inefficiencies that adversely affect productivity, profitability, and food security. Delays in critical processes such as harvesting, transportation, and market distribution primarily drive these inefficiencies (Mohammed et al. 2024). Poor infrastructure, including inadequate road networks and limited cold storage facilities, exacerbates these delays, leading to significant post-harvest losses, particularly for perishable goods. Waste is another major issue, with inefficiencies in logistics and handling contributing to losing up to 40% of agricultural produce before it reaches consumers. Furthermore, the lack of streamlined processes increases operational costs, reducing profit margins for farmers and other stakeholders. These inefficiencies also prevent smallholder farmers from accessing lucrative markets, trapping them in cycles of low productivity and income.

Transparency Issues

A lack of transparency is a pervasive challenge in SSA's agricultural supply chains. Information asymmetry is a key factor, where critical data on market prices, demand, and quality standards are not equally accessible to all stakeholders. This disparity often results in exploitation of farmers, who lack bargaining power and are forced to accept unfair prices from intermediaries (Tang et al. 2024). Fraudulent practices further erode trust within the supply chain. For example, misrepresentation of product quality, adulteration, and counterfeit certifications are common, particularly in export markets. Such practices not only damage the reputation of SSA's agricultural products but also lead to financial losses for stakeholders. The absence of a reliable mechanism to verify and share information across the supply chain perpetuates these transparency issues, hindering efforts to build trust and accountability.

Traceability Concerns

Traceability remains a critical weakness in SSA's agricultural supply chains, posing challenges for both local consumption and international trade. The inability to track produce origins and monitor the supply chain journey undermines food safety, as stakeholders cannot identify and address

contamination or quality issues promptly (Bai, Quayson, and Sarkis 2022).This lack of traceability is particularly problematic for exports, where compliance with stringent international standards is essential. Without reliable tracking mechanisms, SSA's agricultural products struggle to compete in global markets, reducing the region's potential for trade and economic growth. Furthermore, the absence of clear and verified supply chain data reduces consumer confidence, as buyers cannot ascertain the authenticity, origin, or quality of the products they purchase. Addressing these challenges requires innovative solutions that enhance process efficiency, improve transparency, and establish robust traceability mechanisms to build resilient and competitive agricultural supply chains in SSA.

4.2. Blockchain Applications in Agricultural Supply Chains

Enhancing Efficiency

One of the most transformative applications of blockchain technology in agricultural supply chains is its ability to enhance efficiency through automation and real-time data sharing. Smart contracts are a key feature of blockchain that allow for the automation of transactions and processes across the supply chain. These self-executing contracts can automatically trigger actions such as payment releases, inventory updates, or shipment scheduling based on predefined conditions, reducing the need for intermediaries and manual intervention. This not only speeds up operations but also minimizes errors and delays, which are common in traditional systems (Buthelezi et al. 2021). Smart contracts streamline complex agreements, ensuring that all parties meet their obligations in a timely and transparent manner, reducing operational bottlenecks and improving overall efficiency.

Blockchain also facilitates real-time data sharing among all stakeholders in the agricultural supply chain, from farmers to consumers. By utilizing blockchain, all parties have access to the same, up-to-date information, which ensures that everyone involved in the supply chain—from growers to distributors to retailers can make informed decisions based on accurate data. This real-time sharing of transactional and environmental data can help reduce inefficiencies, such as overproduction, underproduction, or unnecessary logistical delays (Cao et al. 2022). Moreover, transaction verification through blockchain ensures that every transaction is recorded securely and transparently, making it easier to verify the authenticity of goods and services throughout the supply chain. This system reduces the time spent on verifying transactions, thus improving the speed and efficiency of the entire process.

Improving Transparency

Blockchain's inherent characteristics make it an ideal tool for improving transparency in agricultural supply chains. The immutability of blockchain records ensures that once a transaction is recorded, it cannot be altered or tampered with. This provides a transparent and verifiable history of every transaction, making it an effective tool for audits and building trust between supply chain participants. By offering a permanent and publicly accessible record of activities, blockchain allows stakeholders, including regulatory bodies and third-party auditors, to verify the integrity of supply chain operations, preventing fraudulent practices and ensuring compliance with established standards (Mavilia and Pisani 2022).

Additionally, blockchain enhances consumer confidence by providing access to supply chain data. By scanning a product's QR code or accessing a blockchain-powered platform, consumers can trace the entire journey of an agricultural product—from its origin at the farm to its arrival at the point of sale. This transparency not only helps consumers make informed purchasing decisions but also ensures that products meet the required ethical, environmental, and quality standards. The ability to verify the source of agricultural goods and their processing history can help combat issues such as food fraud, mislabeling, and unethical production practices, promoting greater accountability in the sector (Zkik et al. 2023).

Enabling Traceability

Blockchain technology plays a critical role in enabling traceability in agricultural supply chains, allowing for the detailed tracking of products from farm to table. With blockchain, each step in the

supply chain—from production to processing, transportation, and retail—can be logged on a secure, immutable ledger, making it easier to trace any item back to its source. This feature is especially important for ensuring food safety, as it allows stakeholders to quickly identify and address any issues, such as contamination or recalls. In the event of a food safety issue, blockchain can help pinpoint the exact source of the problem, reducing the scope of recalls and minimizing the risk of widespread contamination (Quayson et al. 2024).

The integration of Internet of Things (IoT) devices with blockchain further enhances traceability by providing real-time, accurate data on environmental factors like temperature, humidity, and location throughout the supply chain. IoT sensors can be embedded in agricultural products or shipments, recording precise information that is then securely logged on the blockchain (Smidt and Jokonya 2022). This integration enables the precise monitoring of agricultural goods, ensuring that perishable products maintain optimal conditions during transport and storage. By combining IoT's real-time data capabilities with blockchain's immutable record-keeping, the supply chain is not only transparent but also verifiable at every stage. This enhanced precision in tracking improves product quality control and ensures that all participants in the supply chain from farmers to consumers have access to accurate and trustworthy information about the agricultural products they handle.

In summary, blockchain applications in agricultural supply chains, particularly in enhancing efficiency, improving transparency, and enabling traceability, offer significant benefits that can help overcome the persistent challenges facing the sector in Sub-Saharan Africa. These applications provide a foundation for more resilient, sustainable, and equitable agricultural systems.

4.3. Benefits and Impacts

Economic Benefits

The integration of blockchain technology into agricultural supply chains in Sub-Saharan Africa (SSA) offers significant economic advantages (Ronaghi 2021). One of the most prominent benefits is cost savings achieved through streamlined operations and the elimination of intermediaries. By automating processes using smart contracts and ensuring real-time data sharing, blockchain reduces administrative overheads, logistical inefficiencies, and transaction delays. These improvements result in lower operational costs for all stakeholders in the supply chain. Additionally, blockchain helps to reduce wastage by improving the traceability and monitoring of agricultural products, which ensures timely intervention to prevent spoilage or loss (Mohammed et al. 2024).

Another economic benefit is the facilitation of fair pricing for farmers, particularly smallholder farmers who often face exploitation by intermediaries. Blockchain enables direct transactions between farmers and buyers, eliminating the need for middlemen who inflate prices or misrepresent market conditions (Bikoro 2022). With access to transparent market data and secure payment systems, farmers can negotiate better prices for their produce, leading to increased income and financial stability. This equitable pricing mechanism also fosters greater participation in formal markets, enhancing the economic inclusion of marginalized farmers.

Environmental Impacts

Blockchain technology can contribute to significant reductions in food waste, a critical issue in SSA where post-harvest losses are alarmingly high (Kamble et al. 2020). By enabling precise tracking of agricultural products, blockchain ensures that goods are transported, stored, and delivered under optimal conditions. Real-time monitoring facilitated by blockchain-integrated IoT devices helps detect inefficiencies in the supply chain, allowing stakeholders to take corrective actions to prevent spoilage. This not only reduces environmental harm caused by wasted food but also ensures that more resources are utilized effectively to feed growing populations (Lee et al. 2022).

Additionally, blockchain promotes improved resource management by enhancing the efficiency of supply chain operations. By providing accurate and transparent data on resource usage, such as water, energy, and fertilizers, blockchain helps optimize agricultural practices. For instance, farmers can use blockchain data to adopt sustainable farming methods and reduce their environmental footprint (Ronaghi 2021). This is particularly important in SSA, where resource scarcity and climate

change are pressing challenges. The adoption of blockchain can thus support the transition toward environmentally friendly and sustainable agricultural systems.

Social Impacts

The social impacts of blockchain technology in SSA's agricultural supply chains are transformative, particularly in fostering trust among stakeholders. Blockchain's immutable and transparent records eliminate information asymmetry and ensure accountability throughout the supply chain. This increased transparency reduces fraudulent practices, such as misrepresentation of product quality or unfair pricing, creating an ecosystem where all participants from farmers to consumers have confidence in the integrity of transactions (Mukherjee et al. 2022).

Moreover, blockchain technology has the potential to empower small-scale farmers, who form the backbone of SSA's agricultural sector but often remain marginalized in traditional supply chains (Ronaghi 2021). By providing direct access to markets and enabling secure, transparent transactions, blockchain removes barriers that typically disadvantage smallholder farmers. It also facilitates access to financial services, such as loans and insurance, by establishing credible digital records of farmers' transactions and productivity (Kamble et al. 2020). This empowerment not only improves the livelihoods of small-scale farmers but also encourages their active participation in building resilient and inclusive supply chains (Mirabelli and Solina 2020). In summary, the economic, environmental, and social benefits of blockchain technology present a compelling case for its adoption in SSA's agricultural sector. By addressing critical challenges and creating a more equitable, efficient, and sustainable system, blockchain has the potential to transform the region's agricultural supply chains and contribute to broader developmental goals.

4.5. Challenges and Limitations of Blockchain Adoption

Technical Challenges

Despite its potential, the adoption of blockchain technology in Sub-Saharan Africa's (SSA) agricultural supply chains faces significant technical challenges. One major issue is scalability, as many blockchain platforms struggle to handle the large volumes of transactions required in complex supply chains. This limitation can lead to slower transaction processing times and reduced efficiency, undermining the technology's intended benefits (Cao et al. 2022).

Another concern is energy consumption, particularly with blockchain systems that rely on energy-intensive consensus mechanisms like Proof of Work (PoW). In a region where access to reliable and affordable energy is limited, the high energy requirements of blockchain can pose significant barriers to adoption (Rana, Tricase, and De Cesare 2021). Additionally, the integration with existing systems presents a challenge. Many agricultural supply chains in SSA still rely on manual processes and outdated technologies. Transitioning to blockchain requires significant upgrades to infrastructure and compatibility with existing systems, which can be both technically and logistically demanding. Without seamless integration, the implementation of blockchain may disrupt rather than enhance supply chain operations (Salah et al. 2019).

Economic Barriers

The high initial implementation costs of blockchain technology remain a significant barrier for many stakeholders in SSA's agricultural sector. Setting up blockchain systems involves expenses related to hardware, software, training, and infrastructure upgrades. For smallholder farmers and cooperatives with limited financial resources, these costs can be prohibitive, discouraging adoption (Kamble et al. 2020). Moreover, ongoing operational costs, such as transaction fees and system maintenance, may further burden stakeholders, particularly in a region where profit margins in agriculture are already narrow. Without financial support or subsidized solutions, blockchain adoption may remain inaccessible to many in the sector.

Social and Regulatory Concerns

Social acceptance and regulatory frameworks are critical factors influencing blockchain adoption in SSA. A key challenge is the lack of awareness among stakeholders about blockchain technology

and its benefits. Many farmers, intermediaries, and policymakers have limited knowledge of how blockchain works, leading to skepticism and resistance to change. Overcoming these barriers requires targeted education and capacity-building initiatives to demonstrate the technology's value and practical applications (Alkahtani et al. 2021).

The absence of supportive policies and standards is another major limitation. For blockchain to function effectively in agricultural supply chains, governments must establish regulatory frameworks that promote its adoption while addressing concerns about data privacy, security, and interoperability. However, many SSA countries lack clear guidelines for blockchain implementation, creating uncertainty for stakeholders and slowing down progress. Harmonizing blockchain standards across countries and sectors is crucial to ensure its scalability and cross-border applicability (Khan et al. 2022).

In summary, while blockchain offers transformative potential for SSA's agricultural supply chains, its adoption is hindered by technical, economic, and social challenges. Addressing these limitations requires a collaborative effort involving governments (Sharma, Al Khalil, and Daim 2022), private sector players, and development organizations to create an enabling environment that supports blockchain integration and ensures its benefits are accessible to all.

4.6. Barriers to Blockchain Implementation in Sub-Saharan Africa with Case Studies

The adoption of blockchain technology in Sub-Saharan Africa (SSA), particularly in agricultural supply chains, faces significant barriers that vary across countries like Zambia, Malawi, Ethiopia, and Kenya. These barriers include technical, economic, and social challenges, which are exacerbated by the region's unique socio-economic and infrastructural conditions.

Technical Barriers

Infrastructure Deficiency: Many SSA countries, including Zambia and Malawi, lack the digital infrastructure necessary for blockchain implementation. Poor internet connectivity, unreliable electricity supply, and limited access to digital devices hinder blockchain adoption, especially in rural areas where agriculture dominates.

Integration Challenges: In Kenya, while the country has a relatively advanced digital economy, integrating blockchain with existing agricultural systems, many of which are manual or semi-digital, remains a challenge.

Lack of Technical Expertise: Ethiopia faces a skills gap, with few individuals and organizations having the expertise to develop and implement blockchain solutions. The absence of specialized training programs further limits the technology's growth.

Economic Barriers

Blockchain adoption in Sub-Saharan Africa faces significant financial barriers that hinder its widespread implementation. High initial costs, including investment in hardware, software, and training, pose a major challenge, particularly for smallholder farmers in countries like Malawi and Zambia, where such expenses are prohibitive. Governments and cooperatives in these regions often lack the financial capacity to subsidize these investments (Antonucci et al. 2019). Additionally, maintenance and operational costs further impede adoption, even in relatively advanced economies such as Kenya. The ongoing expenses, such as transaction fees and system updates, can be particularly discouraging in agricultural sectors characterized by low profit margins. Furthermore, limited financial inclusion presents another obstacle. In Ethiopia, for example, many small-scale farmers operate within informal economies, making it difficult for them to access the capital necessary for blockchain implementation. These financial challenges highlight the need for targeted strategies, such as subsidies, affordable solutions, and capacity-building programs, to facilitate blockchain adoption in the region's agricultural supply chains.

Social and Regulatory Barriers

Low awareness and resistance to change remain significant barriers to blockchain adoption in Sub-Saharan Africa. In Zambia and Malawi, awareness of blockchain technology among farmers and

other stakeholders is minimal. Resistance to adopting unfamiliar technologies is common, often rooted in mistrust and a lack of demonstrable benefits. Policy and regulatory gaps further complicate the situation, as illustrated by Ethiopia and Kenya. In Ethiopia, the absence of policies governing blockchain use creates uncertainty for investors and developers. Meanwhile, in Kenya, despite the government's expressed interest in blockchain, specific frameworks for its application in agriculture are still underdeveloped (Kamilaris, Fonts, and Prenafeta-Boldú 2019; Shahid et al. 2020). Additionally, cultural and educational barriers present challenges. Limited education and digital literacy in rural areas, such as those in Malawi and Zambia, hinder stakeholders' ability to understand and effectively utilize blockchain. These factors underscore the need for awareness campaigns, regulatory reforms, and educational initiatives to overcome these challenges and promote the adoption of blockchain in agricultural supply chains.

4.7. Case Studies

a) **Zambia**
In Zambia, agriculture contributes significantly to the economy, but supply chains are often inefficient due to poor infrastructure and lack of transparency. Blockchain pilots, such as the use of mobile-based platforms for traceability in maize supply chains, have shown promise. However, these projects are limited by high costs and insufficient digital literacy among farmers.

b) **Malawi**
Malawi faces high post-harvest losses due to inefficiencies and poor storage. Efforts to introduce blockchain for tracking tobacco exports have been met with challenges, including resistance from middlemen who fear losing control over pricing. The lack of reliable internet connectivity in rural areas further complicates implementation.

c) **Ethiopia**
Ethiopia's coffee sector, a critical export industry, has seen attempts to use blockchain for traceability and fair trade. The Ethiopian government partnered with Cardano to create a blockchain-based system for verifying coffee origins. However, these initiatives face scalability challenges due to low farmer participation and high costs.

d) **Kenya**
Kenya's tech-savvy economy and thriving agriculture sector make it a potential leader in blockchain adoption. However, efforts to use blockchain for milk traceability and farmer payments have struggled with integration issues and lack of farmer buy-in. Regulatory gaps also create uncertainty for large-scale implementation.

Recommendations to Overcome Barriers

Infrastructure investment, capacity building, financial support, and collaboration are critical strategies for overcoming barriers to blockchain adoption in Sub-Saharan Africa's agricultural sector. Governments and development partners should prioritize investments in internet connectivity, electricity, and digital tools, particularly in rural areas (Caro et al. 2018). Capacity building through training programs in countries like Ethiopia and Zambia can help bridge the skills gap, enabling local stakeholders to develop and manage blockchain solutions effectively. Subsidies and financial support, such as grants for blockchain projects, can alleviate the cost burden on small-scale farmers and cooperatives in Malawi and Zambia. Furthermore, policy development is essential; establishing clear regulatory frameworks in countries like Ethiopia and Kenya can provide the confidence needed for investment and innovation in blockchain technologies. Lastly, public-private partnerships can play a pivotal role. Collaboration between governments, private sector actors, and NGOs can drive large-scale adoption by pooling resources and expertise, ensuring a more inclusive and sustainable approach to integrating blockchain into agricultural supply chains.

4.8. Future Directions and Opportunities

Development of Scalable and Energy-Efficient Blockchain Solutions

To fully realize the potential of blockchain technology in Sub-Saharan Africa's (SSA) agricultural supply chains, the development of scalable and energy-efficient solutions is critical. Current blockchain platforms often struggle with scalability, limiting their ability to handle the high volume of transactions typical in agricultural supply chains. Future efforts should focus on designing platforms that can accommodate large datasets and transactions without compromising speed or reliability (Kramer, Bitsch, and Hanf 2021; Song et al. 2022).

Energy consumption remains a pressing concern, particularly in SSA (Song et al. 2022), where energy access is limited and costly. Transitioning from energy-intensive consensus mechanisms like Proof of Work (PoW) to more sustainable alternatives, such as Proof of Stake (PoS) or Proof of Authority (PoA), can significantly reduce the energy demands of blockchain systems. Additionally, incorporating renewable energy sources to power blockchain networks presents an opportunity to align technological advancements with environmental sustainability.

Integration with Emerging Technologies like AI, IoB and IoT

The integration of blockchain with emerging technologies such as Artificial Intelligence (AI) Internet of behaviours (IoB) and the Internet of Things (IoT) can further enhance its applications in agricultural supply chains. AI can be leveraged to analyze blockchain data, enabling predictive analytics and decision-making processes that optimize resource allocation, crop production, and logistics. For instance, AI algorithms can predict market trends or identify inefficiencies in the supply chain, helping stakeholders make data-driven decisions (Madumidha et al. 2019).

IoT devices, such as sensors and GPS trackers, can complement blockchain by providing real-time data on environmental conditions, product locations, and storage parameters (Yadav et al. 2020). When integrated with blockchain, IoT ensures that this data is securely recorded and accessible to all stakeholders, enhancing traceability and quality assurance. This combination of technologies creates a robust ecosystem where supply chains are not only transparent but also intelligent, adaptive, and resilient (Hasan et al. 2023).

The benefits of IoB in agriculture are numerous. IoB technologies can help farmers optimize their operations, reducing waste and improving productivity (Kim et al., 2019). Moreover, IoB technologies provide farmers with real-time data, enabling them to make informed decisions about their operations (Brown, 2020). IoB technologies can also help farmers reduce their environmental impact, improving soil health, reducing water usage, and minimizing waste (Davis et al., 2020). Furthermore, IoB technologies can help farmers track the movement and condition of agricultural products, reducing the risk of contamination and improving food safety (Taylor, 2019).

Policy Frameworks to Encourage Blockchain Adoption in Agriculture

Supportive policy frameworks are essential to overcome barriers and foster the widespread adoption of blockchain in agriculture. Governments and regional bodies in SSA need to establish clear regulations that address issues such as data privacy, security, and interoperability (Zhao et al. 2019). Policies should also focus on reducing the financial burden of blockchain implementation, such as by offering subsidies, tax incentives, or funding for pilot projects (Kaijun et al. 2018; Saurabh and Dey 2021).

Additionally, public-private partnerships can play a vital role in driving blockchain adoption. Collaborations between governments, technology providers, and agricultural organizations can facilitate knowledge sharing, resource pooling, and the development of tailored solutions for SSA's unique challenges. Educational initiatives to improve blockchain literacy among farmers, intermediaries, and policymakers are equally important (Saurabh and Dey 2021). Training programs and awareness campaigns can help stakeholders understand the benefits of blockchain and build confidence in its implementation. The analytical results of this study show novelty in finding that the integration of blockchain with smart contracts and IoT not only improves transparency but also provides specific solutions to the challenges of limited infrastructure in SSA. Unlike previous research that tends to focus on developed countries, this study offers an adaptive approach through low-cost and community-based technology-based solutions. For example, the use of simple IoT devices to log real-time environmental data and record it on the blockchain allows smallholder

farmers to participate without the need for large investments. In summary, the future of blockchain in SSA's agricultural supply chains lies in addressing scalability and energy challenges, leveraging synergies with emerging technologies, and creating an enabling regulatory environment. These efforts will ensure that blockchain contributes to a more efficient, transparent, and inclusive agricultural sector, driving sustainable development across the region (Kraft and Kellner 2022).

5. Conclusion

Blockchain technology holds transformative potential to address the persistent challenges in Sub-Saharan Africa's (SSA) agricultural supply chains. By enhancing efficiency, improving transparency, and enabling traceability, blockchain offers innovative solutions to inefficiencies, fraud, and information asymmetry. It empowers smallholder farmers, reduces post-harvest losses, and fosters trust among stakeholders. The integration of blockchain can significantly enhance the region's agricultural productivity, market access, and overall economic resilience.The technology's potential to revolutionize SSA's agricultural sector cannot be overstated. Blockchain provides a robust framework for creating supply chains that are not only efficient but also equitable and sustainable. Its applications, particularly when integrated with emerging technologies like AI and IoT, can usher in a new era of data-driven, transparent, and resilient agricultural practices. Moreover, blockchain's capacity to address critical issues such as food safety, fair pricing, and environmental sustainability positions it as a game-changer for the region. However, realizing this potential requires collaborative efforts across multiple fronts. Governments, private sector players, research institutions, and development organizations must work together to overcome technical, economic, and social barriers to blockchain adoption. Investments in research, capacity building, and infrastructure development are critical to ensuring that blockchain solutions are accessible and scalable. Equally important is the need for policy frameworks and standards that foster innovation while addressing ethical and regulatory concerns. In summary, blockchain technology offers an unprecedented opportunity to transform SSA's agricultural supply chains. By embracing this innovation through coordinated efforts, the region can build more resilient, transparent, and efficient systems that drive sustainable development and improve livelihoods across the agricultural sector.

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