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Review article

Assessing blockchain and IoT technologies for agricultural food supply chains in Africa: A feasibility analysis

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ABSTRACT

This review paper delves into the global agricultural food supply chains through the lens of African perspectives, examining the role of blockchain and Internet of Things (IoT) technologies in transforming food traceability. It assesses the applicability and efficacy of these innovations in addressing critical issues such as food fraud, contamination, and systemic inefficiencies from an African viewpoint. By engaging in an in-depth analysis of relevant studies, this work dissects the technical, economic, legal, and operational facets of employing blockchain and IoT in the agri-food sector. The findings illuminate the transformative potential these technologies hold for enhancing food safety and transparency across supply chains. However, the review also brings to light significant hurdles related to scalability, cost-effectiveness, and regulatory frameworks that must be surmounted. Advocating for a context-sensitive application of blockchain and IoT, the paper highlights the importance of adapting these technologies to fit the diverse socio-economic and infrastructural realities prevalent in African countries. Offering valuable insights to stakeholders in agricultural technology and food safety, this comprehensive review outlines a roadmap for future research and strategic implementation efforts aimed at leveraging blockchain and IoT for the development of secure, sustainable food systems.

1. Introduction

In an era where food safety and traceability are of paramount importance, the integration of advanced technologies like blockchain and the Internet of Things (IoT) into food supply chains has become increasingly relevant. The global food industry, facing challenges such as food fraud, contamination, and ineficient supply chain management, is in dire need of innovative solutions to ensure the safety, integrity, and transparency of food products from farm to table.

In one notable case [1] in South Africa, several children tragically lost their lives after consuming snacks from informal retail outlets, known as spaza shops. These heartbreaking incidents, which include fatalities and serious illnesses among young students from various schools, have drawn attention to the critical vulnerabilities in food supply chains, particularly in the informal sector. Such

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episodes not only result in devastating health consequences but also erode public trust in food safety standards. The inability to swiftly trace and address the source of these contaminants points to a dire need for more effective food tracking and safety mechanisms.

Another notable case [2] of food fraud involves tomato powder. In Ghana, genuine tomato powder typically exhibits a less vibrant red hue due to the processing method. However, a 2016 report [3] by the Ghana Food and Drug Authority (FDA) disclosed that much of the tomato powder in the local market was adulterated with annatto seeds, misleading consumers about its authenticity. Similarly, honey in Ghana has been found adulterated with substitutes like molasses, roasted corn, and sugar, significantly deviating from its natural composition. The adulteration [4] of palm oil is another pressing concern. The widespread use of Sudan IV dye, known locally as "shuudin," has been a common practice. A 2021 market survey [5] by the FDA identified this dye as a primary adulterant in palm oils, posing health risks to consumers. This adulteration not only compromises the quality of palm oil but also raises serious health concerns.

Additionally, the use of calcium carbide to hasten the ripening of fruits and vegetables has been reported [6], rendering these foods highly toxic. This practice reflects a dangerous shortcut in food preparation that prioritizes appearance and marketability over consumer safety.

A comprehensive study [2] in Tamale shed light on the extent of food fraud in the region, implicating a range of products, including beverages, juices, spices, oils, meat, fish, and several semi-processed local foods. The study revealed the use of "Moora" (Bixa orellana seeds) as a common adulterant, employed to impart an appealing reddish hue to various foods. The prevalence of strategies like adulteration, tampering, substitution, and mislabeling was noted, indicating a systematic issue within the local food industry.

Finally, the recent tragic event [7] outside Nigeria's capital, where young lives were lost due to food adulteration, underscores a dire and escalating global crisis within our food supply chains. This incident is a somber reminder of the broader, pervasive challenge of food fraud—a deliberate act by companies to deceive consumers about the quality or origin of their food products. The Grocery Manufacturers Association in the United States estimates that food fraud affects approximately 10 percent of all commercially sold food products worldwide, inflicting an economic toll of $10 to $15 billion annually on the global food industry. While comprehensive data for Africa is scarce, the available information paints a concerning picture. For instance, the Confederation of Tanzania Industries estimates [8] that over 50 % of all imported goods, including food, are counterfeit.

The efforts of regulatory bodies such as the FDA and the Ghana Standards Authority (GSA) have been pivotal in addressing food fraud in Ghana. Their joint actions, including enforcement operations and public awareness campaigns, have led to several successes, such as the arrest of individuals involved in selling counterfeit alcoholic beverages and the seizure of substandard imported canned tomatoes. However, the ongoing prevalence of food fraud suggests that more robust measures and continual vigilance are required to combat this issue and safeguard public health effectively.

This situation in Ghana highlights a critical need for enhanced food safety measures and traceability systems. The implementation of advanced technologies like blockchain and IoT could significantly bolster efforts to monitor food authenticity and safety, offering promising solutions to tackle the complex challenge of food fraud in the country.

Likewise, the events in South Africa illustrate a broader, global challenge in ensuring food safety, highlighting the potential role of innovative technologies like blockchain and IoT in revolutionizing food traceability.

In the face of such daunting challenges, this paper seeks to explore the potential of blockchain and Internet of Things (IoT) technologies as innovative solutions to enhance traceability and integrity within agricultural food supply chains globally, with a particular focus on the African context. This research not only highlights the transformative potential of blockchain and IoT in addressing these critical issues but also identifies the primary obstacles to their widespread adoption, such as scalability, cost, and

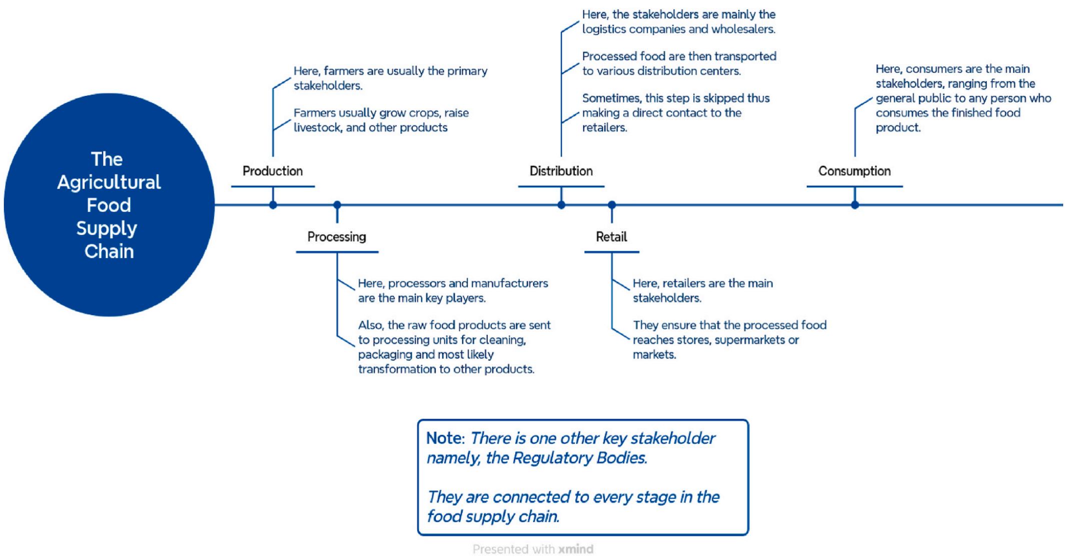

Fig. 1. The agricultural food supply chain.

regulatory compliance. While the systematic literature review conducted by Ref. [9] provides an in-depth examination of the technical implementation aspects of blockchain-enabled supply chain traceability systems, including an assessment of their implementation maturity, technical details, and the sustainability dimensions (economic, environmental, and social) associated with these implementations, their study did not consider both blockchain and IoT technologies; thus, the current paper shifts focus. This paper presents a comprehensive review of the feasibility studies concerning the adoption of blockchain and Internet of Things (IoT) solutions in global agricultural food supply chains, specifically from an African perspective. Also, this review aims to explore the practicality, benefits, and challenges of implementing these cutting-edge technologies within the context of Africa's unique socio-economic and infrastructural landscapes, offering insights into their potential to transform food safety and traceability across the continent.

2. Agricultural food supply chain

The agricultural food supply chain, also known as the agri-food supply chain, refers to the complex network of processes as depicted in Fig. 1. While others usually have the regulatory body right after the processing stage, the regulatory body is actually needed at every stage of the entire food supply chain, monitoring conditions and putting up measures that will make the food product safe during consumption.

3. Blockchain technology

Blockchain technology is a decentralized digital ledger system that records transactions across many computers in such a way that the registered transactions cannot be altered retroactively. This technology is characterized by its decentralized nature, immutability, transparency, and security. Each block in a blockchain contains a number of transactions, and every time a new transaction occurs, a record of that transaction is added to every participant's ledger. This makes blockchain technology a reliable system for recording and verifying data.

The key components of blockchain technology include.

- Decentralization: Unlike traditional databases, blockchain operates on a peer-to- peer network where each participant maintains a copy of the ledger.
- Immutability: Once a transaction is recorded in a block and added to the blockchain, it cannot be altered or deleted, ensuring data integrity.
- Transparency: All participants in the network have access to the blockchain and can verify transactions independently.
- Security: Transactions are encrypted and linked to the previous transaction, making the blockchain resistant to tampering and fraud.

There are several types of blockchain technologies, each designed to meet different needs and use cases. Public blockchains are open to everyone and are fully decentralized. Anyone can participate in the network, validate transactions, and create new blocks. Examples include Bitcoin and Ethereum. Private blockchains, on the other hand, are restricted and are usually used within a single organization or a group of organizations. Access is controlled, and only authorized participants can validate transactions and create new blocks. Examples include Hyperledger Fabric and Quorum. Consortium blockchains are semi-decentralized and are controlled by a group of organizations rather than a single entity. They offer partial decentralization, providing more control than public blockchains but more openness than private blockchains. Examples include R3 Corda and Energy Web Foundation. Hybrid blockchains combine elements of both public and private blockchains, allowing for controlled access while still maintaining some level of transparency and decentralization. An example of this type is Dragonchain.

3.1. Blockchain technology in food supply chains

Blockchain technology is revolutionizing the food supply chain with its decentralized, immutable ledger system. It ensures a tamper-proof record of every transaction, from the farm to the consumer, making the history of each food product transparent and traceable. This level of transparency is vital for quickly pinpointing sources of contamination or identifying counterfeit products, thereby significantly enhancing food safety and bolstering consumer confidence. Furthermore, blockchain's ability to seamlessly integrate with other technologies and systems adds to its versatility in supply chain management. It enables the creation of a holistic ecosystem where data integrity and security are maintained, fostering a safer and more reliable food supply chain. While blockchain technology brings transparency and trust, mistrust could likely occur due to the manual data entry into solutions that employ blockchain. This will cause the blockchain platform to track falsified and erroneous information with a particular supply chain, in our case, the food supply chain. However, due to the seemingly high level of integration of the blockchain platform with other technologies, this seems not to be a huge problem, as the subsequent section presents a solution to this problem.

4. Internet of things

The Internet of Things (IoT) refers to a network of interconnected devices that collect, exchange, and act on data, often without human intervention. These devices, from simple sensors to complex systems, communicate over the internet or other communication networks. IoT technology is transforming various industries by enabling smarter operations, real-time monitoring, and data-driven decision-making.

The Internet of Things (IoT) is pivotal in modernizing the food supply chain. IoT devices, including sensors such as wireless sensor networks, installed cameras, RFID tags, and the like, offer real-time monitoring capabilities for various critical parameters, such as temperature, humidity, and geographical location. This continuous data stream allows stakeholders to proactively manage and maintain optimal conditions at every stage of the supply chain. Integrating IoT technologies in the food industry is instrumental in reducing waste, minimizing spoilage, and ensuring that food products retain their quality and freshness up to the point of consumption. Moreover, IoT data can feed into blockchain systems, creating a synergy that enhances overall supply chain efficiency and reliability. As a result, the possibility of human error being introduced onto the blockchain network becomes relatively low. This integration empowers stakeholders with actionable insights, facilitating informed decision-making and fostering a more resilient and responsive food supply network.

The combination of blockchain and IoT technologies addresses several key issues in food supply chains.

- Enhanced Traceability: Together, they provide end-to-end visibility of the supply chain, allowing for efficient tracking of food products from origin to consumption.
- Improved Food Safety: Rapid identification of safety breaches becomes possible, significantly reducing the risk of large-scale foodborne illness outbreaks.
- Increased Efficiency: Automated and streamlined processes reduce manual errors and operational costs.
- Consumer Confidence: Transparent and accurate information about food origin and handling boosts consumer trust and satisfaction.

Despite their potential, implementing blockchain and IoT in food supply chains, especially in regions like Africa, poses unique challenges. These include technological infrastructure, cost considerations, legal compliance, and operational practicality. Thus, a comprehensive review is needed to assess the feasibility of these technologies in improving food supply chain management, particularly focusing on their applicability in different contexts.

5. Methodology

Thus, this review aims to bridge this knowledge gap by systematically analyzing existing literature on the application of blockchain and IoT in food supply chains. It evaluates their technical, economic, legal, and operational feasibility, providing valuable insights for stakeholders and suggesting directions for future research and implementation strategies.

5.1. Data sources

This review considered literature from five research databases, as depicted in Table 1.

The search keywords considered for the review are as follows:

- blockchain
- iot, iiot or internet of things
- traceability or tracking
- food safety, food monitoring, and food quality
- agriculture
- supply chain
- smart contracts
- decentralized
- Web3

To obtain a comprehensive list of literature for this review work, a carefully curated list of search strings was derived from the search keywords. As depicted in Table 1, the derived search strings and their returned results with respect to each search string are shown. Subsequent steps to acquire the necessary papers for the review are succinctly outlined in Fig. 2, providing a clear roadmap for

Table 1
Search results for blockchain technology in various databases.

Search Strings	IEEE Xplore	Elsevier Scopus	Elsevier ScienceDirect	PubMed	Google Scholar
(“blockchain” OR “smart contracts” OR “decentralized” OR “Web3”) AND (“IoT” OR “internet of things”) AND (“traceability” OR “tracking”) AND (“food safety” OR “food quality”)	75/69	80/76	495/667	14/14	9740/8950
(“blockchain” OR “smart contracts” OR “decentralized” OR “Web3”) AND (“IoT” OR “internet of things”) AND (“traceability” OR “tracking”) AND “agriculture”	97/93	123/117	1866/1771	15/9	30,000/18,100
(“blockchain” OR “smart contracts” OR “decentralized” OR “Web3”) AND (“IoT” OR “internet of things”) AND (“traceability” OR “tracking”) AND “supply chain"	449/429	497/476	3242/3084	25/24	34,150/18,800

the literature acquisition process.

The search methodology employed for this review is concisely represented in the table using the format A/B, where 'A' denotes the initial number of search results, 'B' represents the results remaining after applying a five-year temporal range (2019–present). Later, Zotero, a reference management software, is used to remove duplicates as a preparation for the title, abstract and full-text screening of the studies.

Algorithm 1
Screen Selected Paper Titles

```
Require: A bibliographic database file (bib_file)
Ensure: A list of the selected bibliographic entries (screened_entries)
Import the bibtexparser library
function screen_titles(bib_file)
  Open bib_file in read mode
  Load the bibliographic data using bibtexparser
  Initialize screened_entries as an empty list
  for each entry in bib_database.entries do
    title ← Retrieve and convert the title to lowercase
    keywords ← Retrieve and convert keywords to lowercase
    if ('food' in title) and (('blockchain' in title) or ('iot' in title) or ('internet of things' in title)) then
      Append entry to screened_entries
    else if ('blockchain' in title) and ('iot' in title) then
      Append entry to screened_entries
    end if
  end for
  return screened_entries
end function
```

5.2. Screening mechanisms

In the review process, three additional screening mechanisms were employed to refine the selection of papers further. Moreover, we are guided by the PRISMA [10] standard for this review, as shown in the flow diagram in Fig. 2.

The first of these mechanisms was title screening. Given the impracticality of manually screening the titles of all papers, a Python script was developed to automate this task. This script, whose details are illustrated in Algorithm 1, efficiently filtered the titles, yielding a more manageable number.

Following title screening, the next phase involved abstract screening. Similar to the previous step, this process was also automated using a Python script, as shown in Algorithm 2. A key criterion implemented in this script was the identification of the terms "proposed" or "implemented" within the abstracts. This criterion was chosen to focus on papers that contribute concrete proposals or implementations in the field.

The final phase of the literature review involved a meticulous full-text screening process, which was conducted manually to ensure adherence to clearly defined criteria.

The initial stage of full-text screening utilized SCISPACE AI, an innovative application that facilitates interaction with research papers through specific queries. This tool was employed to extract targeted information from each paper by posing the following questions.

- What supply chain is considered in this paper?
- Which food use case is the focus of this research?
- What are the key results of the proposed food traceability system?

Algorithm 2
Screen Paper Abstracts

```
Require: A bibliographic database file (demo_output_final.bib)
Ensure: A list of bibliographic entries with desired phrases (relevant_papers)
Import the bibtexparser library
Import the regex (re) library
function strip_special_characters2(text)
  Use regex to remove any special characters from text
  return the cleaned text
end function
function screen_abstracts(bib_file)
```

(continued on next page)

Algorithm 2 (*continued*)

```
Open bib_file as bibtex_file in read mode
Load the bibtex_file into bib_database using bibtexparser
Define desired_phrases as a list containing "proposed", "implemented"
Initialize relevant_papers as an empty list
for each entry in bib_database.entries do
    abstract ← Retrieve the abstract from the entry, if available
    abstract ← strip_special_characters2(abstract)
    for each phrase in desired_phrases do
        if phrase is in abstract.lower then
            Append the entry to relevant_papers
        end if
    end for
end for
return relevant_papers
end function
```

Papers that did not align with the agricultural food supply chain were systematically excluded. For instance, studies focusing on the additive manufacturing supply chain, despite their prevalence, were deemed irrelevant to the review's scope and thus rejected. Similarly, papers that failed to incorporate food as a use case were also removed from consideration.

The review further discounted papers that solely proposed theoretical frameworks or architectures without any practical implementation, as these studies offer limited insight into the real-world feasibility of the proposed systems.

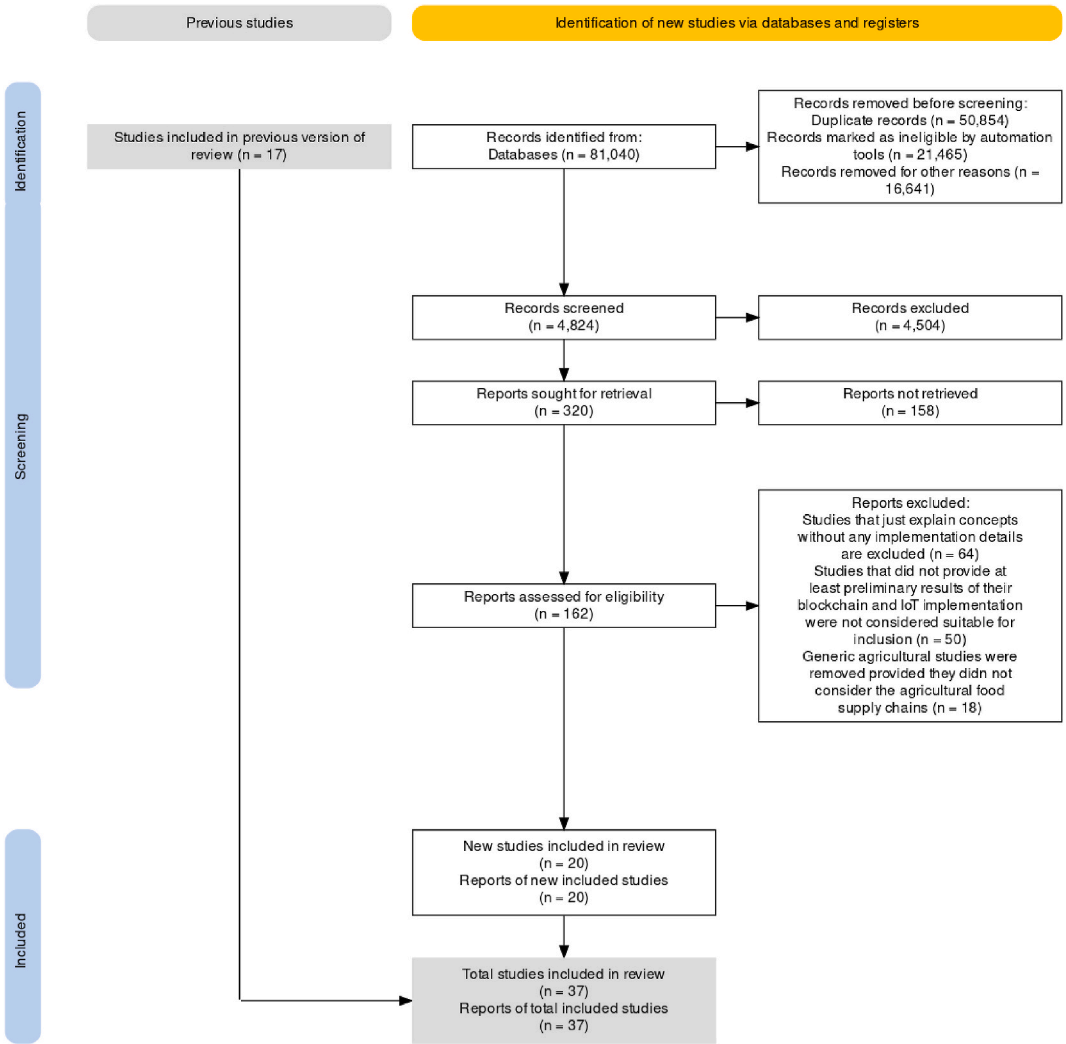

Fig. 2. Using PRISMA to select the papers.

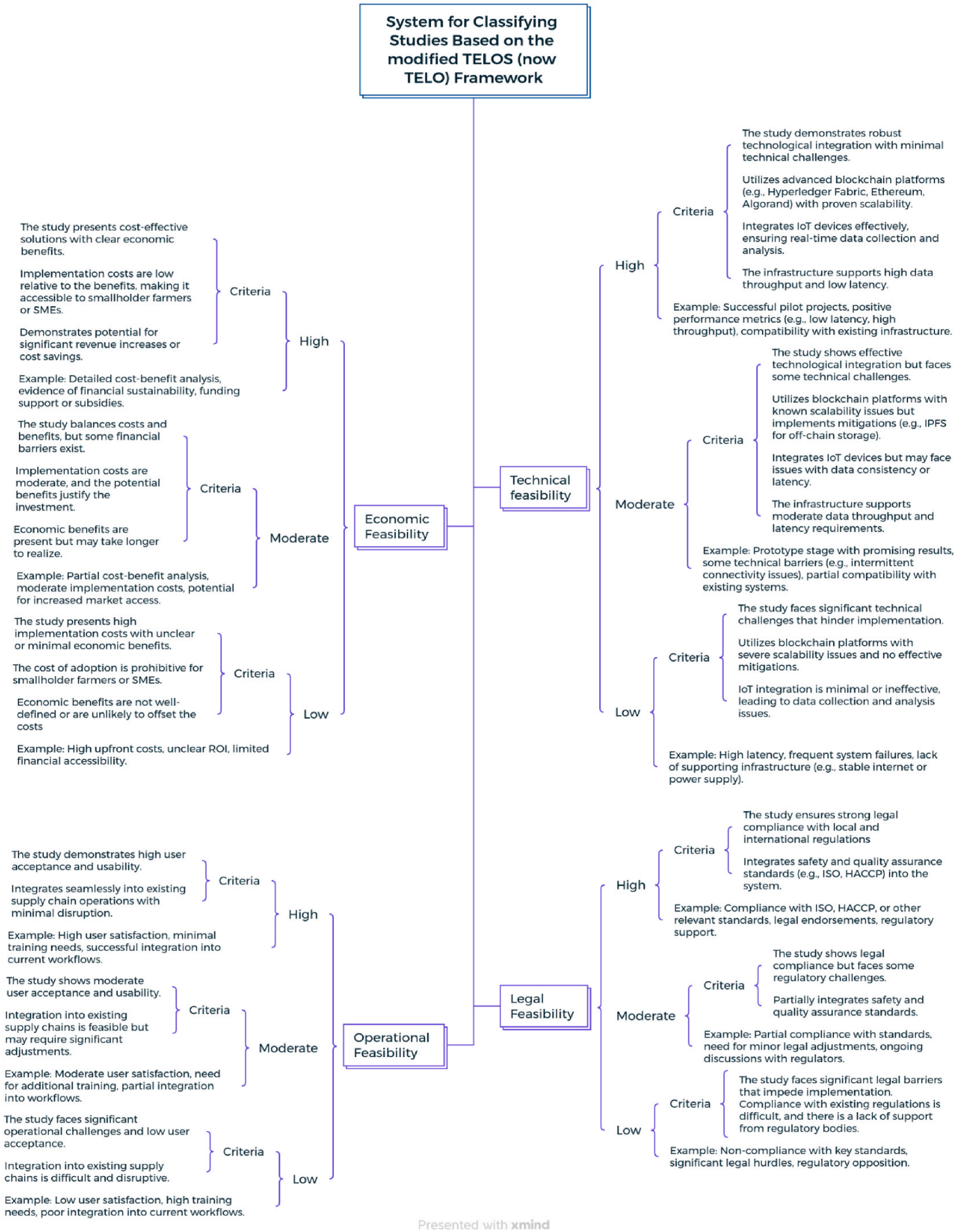

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Fig. 3. Telo framework used for classifying the studies.

- Technical Feasibility: From the study [16], we gain insight into the significant infrastructural limitations—including inconsistent electricity and internet access—that can impede the deployment of IoT technologies. Consequently, our framework places a strong emphasis on assessing existing infrastructural capacities and advocating for the development of adaptive technologies that can function effectively under the resource-limited conditions prevalent throughout the continent. Prioritizing infrastructure enhancements is crucial to enable the successful implementation of advanced technologies. This aspect of the analysis evaluates the technological capabilities and infrastructural support necessary for the deployment of both blockchain and IoT solutions within the African context. It involves a thorough assessment of the scalability of blockchain platforms and the latency requirements of IoT devices. Additionally, it examines the current infrastructure's capacity to adequately support these technologies, ensuring that the proposed solutions are feasible and effective given the local constraints.
- Economic Feasibility: The study [15] brings to light the financial barriers faced by smallholder farmers. The TELO framework, therefore, evaluates not only the direct costs associated with implementing blockchain and IoT but also considers broader economic impacts, such as potential increases in market access and financial inclusivity through improved agricultural finance models. These insights are crucial for developing cost-effective solutions that are financially viable for smallholder farmers. Thus, the economic analysis considers the costs and benefits related to the implementation of blockchain and IoT. This includes direct costs and extended benefits, such as potential revenue increases for stakeholders and impacts on consumer satisfaction. It also emphasizes creating cost-effective solutions that address financial constraints and aim to enhance food security, reduce food waste, and bolster local economies.
- Legal Feasibility: In Ref. [14], the varied regulatory landscapes across African countries are discussed, which could affect the adoption of new technologies. Our framework includes a thorough examination of local and national regulations to ensure that any proposed digital solutions are compliant and can seamlessly integrate into existing legal frameworks. Understanding and navigating these varied regulations are vital for the successful deployment of blockchain and IoT technologies. The legal component focuses on regulatory compliance and includes the following considerations:

The subsequent full-text screening stage entailed a more thorough and traditional approach: a comprehensive reading of each paper's abstract, proposed architecture, and, where applicable, the implementation and results sections. Papers that outlined a proposed architecture, system, or model but did not present any demonstrable results were typically not included in the final review. In contrast, studies providing at least preliminary results were deemed suitable for inclusion. Notably, special attention was accorded to papers that explored blockchain platforms outside the mainstream decentralized domain, recognizing their potential for novel technological applications.

Following these rigorous criteria for full-text screening, the final count of papers deemed relevant and suitable for this review was narrowed down to 37.

6. Actual review

The purpose of this review is to critically evaluate the feasibility of blockchain and Internet of Things (IoT) technologies within the agricultural food supply chain, focusing specifically on the African context. In conducting a systematic assessment of various implementations in these supply chains, we adapted and modified the traditional TELOS (Technical, Economic, Legal, Operational, and Scheduling) feasibility framework to a more streamlined TELO (Technical, Economic, Legal, and Operational) framework by omitting the "Scheduling" component. This refinement was informed by a thorough examination of academic articles and practical case studies pertinent to deploying innovations within African agricultural supply chains.

Adapting the TELO framework arose from specific challenges and opportunities identified in recent studies [11–16] focusing on the African agricultural sector. These studies underscore the significant challenges associated with the digitization of agriculture in Africa, highlighting key technical, economic, legal, and operational barriers and opportunities.

Before delving into the assessment of specific studies, it is crucial to delineate the components of the TELO framework employed in this review, which focuses on the Technical, Economic, Legal, and Operational feasibility of blockchain and Internet of Things (IoT) technologies within the agricultural-food supply chain in Africa.

- o Examination of adherence to safety and quality assurance standards such as ISO and HACCP.
- o Integration of regulatory bodies within proposed architectures or systems to ensure compliance with pertinent laws and regulations. This is particularly important given the diverse legal landscapes across African nations.

- Operational Feasibility: The [12] highlights the disparities in technological literacy among farmers. Thus, this final component assesses user acceptance and usability, which are critical for the practical implementation and effectiveness of blockchain and IoT solutions in the African agricultural food supply chain. It involves tailoring solutions to fit the local context, taking into account factors such as literacy levels, technical skills, and cultural practices.

To further strengthen this framework, insights from additional studies such as [17] highlight the practical applications and benefits of blockchain in improving traceability and operational efficiency in small cooperatives. These examples underline the importance of adaptable and scalable solutions that are designed with a deep understanding of local needs and constraints. This systematic framework, illustrated in Fig. 3, aids in the assessment of global implementations of blockchain and IoT solutions in African agricultural food supply chains, considering the unique challenges and opportunities identified. By leveraging these insights, we can ensure a more robust and comprehensive evaluation of technology deployments, enhancing the credibility and practical relevance of our findings within the agricultural sectors of Africa.

Before applying the TELO framework to the selected studies, we conducted a brief analysis of each study, examining the various technologies employed—blockchain, IoT, or a combination of both. We also looked into different food use cases and supply chains. Fig. 4 illustrates implementations that utilize either blockchain or IoT technologies, along with the specific food supply chains considered. Subsequently, Fig. 5 presents studies that have successfully integrated both blockchain and IoT technologies to provide comprehensive solutions.

Starting with specific African studies, Fig. 6 provides a summary of state-of-the-art (SOTA) blockchain and IoT technology implementations in Africa. As depicted, while there are relatively fewer articles specifically targeting agricultural food supply chains in the African continent, several review papers do mention relevant implementations, making these studies highly significant. It is evident that the integration of blockchain and IoT in the agricultural food supply chain is more prominent in Ghana and South Africa. Consequently, the first 12 studies in Table 2 focus on Afrocentric solutions, while the remaining entries analyze global (external to Africa) solutions involving blockchain and IoT technologies in agricultural food supply chains. This table expands upon Fig. 4 by encompassing all referenced articles and additionally provides a detailed analysis of the strengths and weaknesses of each study. Moreover, the level of integration is assessed based on the classification system highlighted in Fig. 3.

Following a comprehensive analysis of blockchain and IoT technologies, as outlined in Table 2, we conducted a detailed assessment of their technical, economic, legal, and operational feasibility within African agricultural food supply chains. This assessment is informed by the categorization presented in Fig. 3. The consolidated results from these studies are efficiently visualized in the heatmap displayed in Fig. 7. In this heatmap, the feasibility scores are quantified as follows: 'High' corresponds to a score of 3, 'Moderate' to 2, 'Low' to 1, and 'Not Specified' to 0.

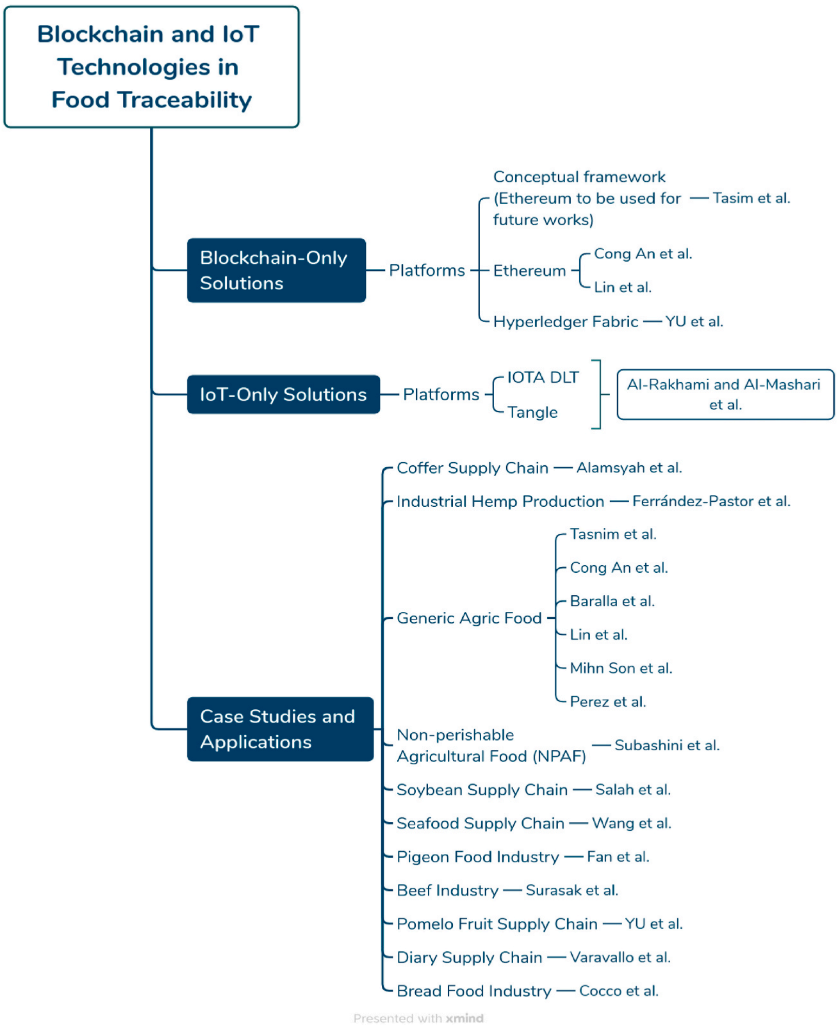

Fig. 4. Mapping the technological landscape: Blockchain-only or IoT-Only solutions in the agricultural food supply chains.

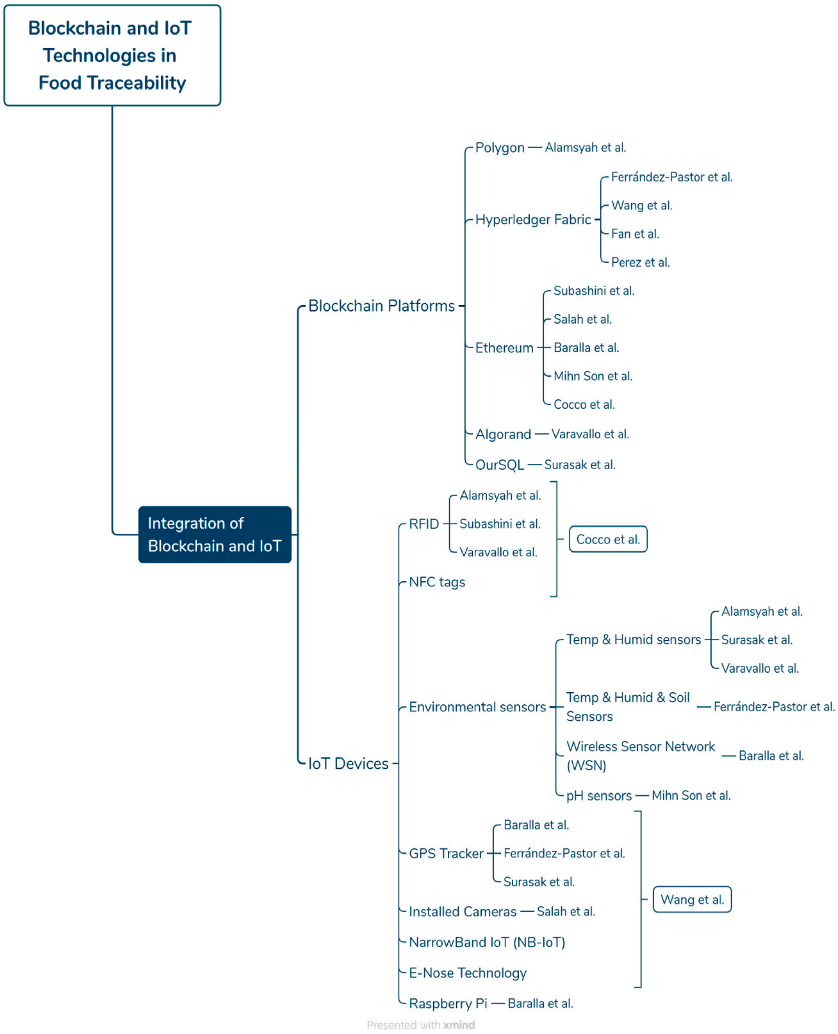

Fig. 5. Mapping the technological landscape: Blockchain and IoT in the agricultural food supply chains.

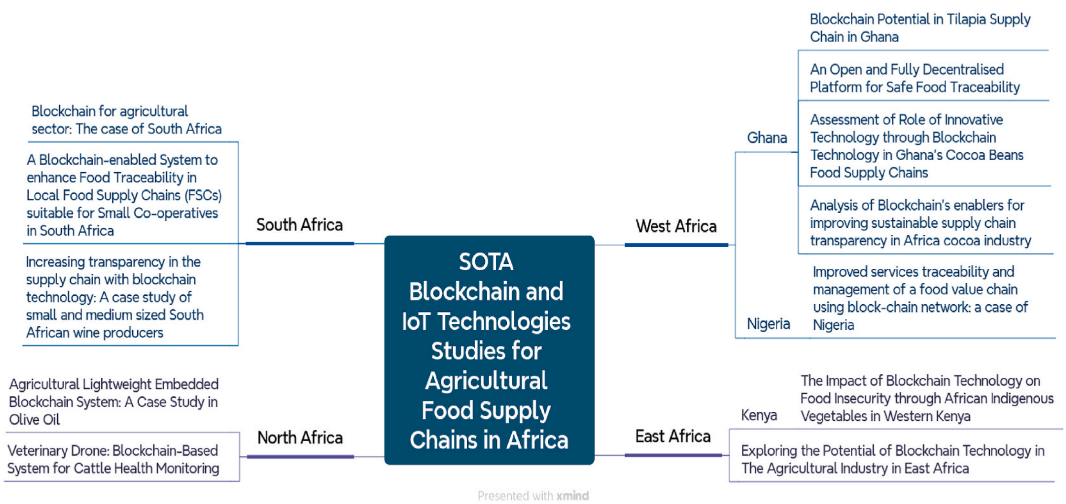

Fig. 6. Summary of SOTA Blockchain and IoT studies for the Agricultural Food Supply Chain in Africa.

Table 2
Summary of blockchain and IoT studies in food traceability.

Study	Specific Supply Chain	Level of Integration	Strengths	Weaknesses
[18]	Olive Oil	Moderate	Uses multi-Blockchain system (Quorum and Ethereum), low power consumption with Rasp- berry Pi and Arduino, inte- grates IoT for real-time data collection	High initial implementation costs, complexity in integrat- ing existing systems, need for training and digital literacy among stakeholders, potential resistance from traditional stakeholders
[19]	Tilapia	High	Real-time monitoring, RFID tags for authenticity, enhanced traceability and reduced fraud	High initial implementation cost, requirement for internet connectivity and digital lit- eracy, potential resistance to technology adoption
[20]	Palm oil	High	multi-asset system, Scalable blockchain solution, real-time responsiveness, implemented prototype	Complexity in implementation, potential challenges in integrat- ing diverse stakeholders
[21]	Cocoa	Moderate	Improves supply chain *trans*- parency, enhances sustainabil- ity, real-time access to prices	High initial investment, com- plexity in integrating with exist- ing systems, complex decision- making process
[22]	Cocoa	High	Reduces deforestation, child la- bor, forced labor, increases transparency	Requirement for training and education, potential resistance from traditional stakeholders
[23]	Wine Industry	Moderate	Reduce the heavy administra-tive workload associated with compliance and certifications, which is particularly taxing for smaller wineries, improve the traceability of wine products by providing a transparent and im- mutable record of wine produc- tion and distribution, which is crucial in a sector plagued by issues of counterfeit wines and quality assurance	complexity associated with blockchain technology that re- quires a high level of technical understanding, cost of imple- menting blockchain technology could be prohibitive for small to medium-sized enterprises, which dominate the South African wine industry
[24]	Rice	Moderate	Fully decentralized framework, sensor-based framework, accu- rate data reporting, integrates RFID for better data manage- ment	Potential resistance from tra- ditional stakeholders, require- ment for training and educa- tion, issues with internet con- nectivity in rural areas
[25]	Cattle health mon- itoring	Moderate	integrates UAVs and IoT for real-time data collection, uses Sui blockchain for secure data storage	need for continuous mainte- nance of IoT devices and UAVs, complexity in integrating exist- ing systems
[26]	African indigenous vegetables	High	Improves food security, reduces post-harvest loss, incentivizes production of high-quality veg- etables	Challenges in scaling to broader regions without infrastructure support, requirement for smart- phone ownership and digital lit- eracy
[27]	Fair-trade food	Moderate	Improved traceability and certi-fication processes	Complexity and requirement of multidisciplinary expertise to implement efficiently, requires a redesign of existing infrastruc- ture to align the interests of all parties involved in the food sup- ply chain
[17]	Generic Agric-food	High	Enables traceability and transparency to smallholder farmers, hybrid solution of web/blockchain implemented	Lack of awareness expressed by the farmers and consumers on the use BCT for food trace- ability, ensuring that the ini- tial data entry into a blockchain platform is truthful since there was no IoT integration
[28]	Grape	High	Capable of tracing the certifi- cates in the supply chain of ta- ble grapes	Infrastructure must be re- designed for the modern economy, partnerships with Blockchain technology related service providers are required
[29]	Traditional Italian bread (Carasau)	High	Leverages Blockchain and IoT (RFID, NFC), reduces data en- try errors, ensures hygiene com- pliance with HACCP	Potential scalability issues with large datasets
[30]	Seafood	High	Real-time monitoring of fish quality (temperature, location), enhances operational efficiency, reduces labor costs	Complexity in maintaining pri- vacy while enabling data shar- ing
[31]	Wine industry	Moderate	Focuses on counterfeiting, ex-plores economic and operational implications, re-engineers exist- ing systems	Prototype stage, yet to fully address large-scale operational challenges
[32]	Dairy (Fontina PDO cheese)	High	Uses Algorand's Pure Proof- of-Stake, minimizes ecological footprint, IoT for accurate data collection	Complexity in integrating exist- ing systems with blockchain, re- quirement for training and dig- ital literacy among operators
[33]	Beef	High	Real-time monitoring, uses IoT devices, supports compliance with food safety standards (GMP, HACCP, HALAL), integrates blockchain with IoT for real-time monitoring	Complexity in integrating ex- isting systems with blockchain, high implementation costs
[34]	Urban fruit	High	Focuses on efficient and se-cure design, uses blockchain for asymmetric encryption and smart contracts	high cost in buying RFID equip- ment, need for precise and trustworthy data
[35]	Generic Agric-food	High	Scalable, tamper-proof system, enterprise-level smart contracts, manages on-chain and off-chain data	Complex implementation, scalability challenges
[36]	Generic Agric-food	High	Automated data collection and storage, smart contract-based, ensures data integrity and au- thenticity	Specific challenges related to agricultural sector data collection and traceability

(*continued on next page*)

Table 2 (*continued*)

Study	Specific Supply Chain	Level of Integration	Strengths	Weaknesses
[37]	Olive oil and general agri-food products	High	Comprehensive multi-layered solution integrating Hyper- ledger Fabric and IoT devices, modular and scalable, provides secure and permanent record of transactions, user-friendly with smart contracts (Foodchain)	High initial implementation costs, complexity in integrat- ing existing systems, need for training and digital literacy, potential resistance from traditional stakeholders
[38]	General agri-food products	High	Uses Hyperledger Fabric for se- cure and efficient data handling thus, highly scalable, supports multi-layered traceability solutions, adaptable to various agri-food supply chains	The main problem could be the high memory capacity that the machine in use must have to be able to memorize the blocks of the chain, to which new information will be added each time.
[39]	General agri-food products	High	Uses private blockchain network built on Ethereum and Go- Quorum protocol, supports se- cure and decentralized data ex- change	technical challenges in long- distance data transmission, complexity in integrating exist- ing systems

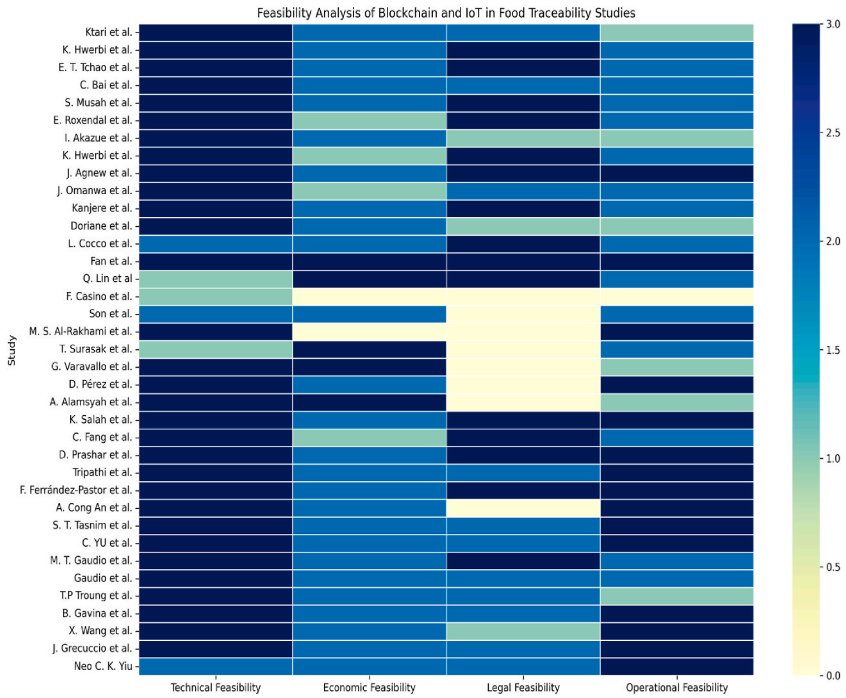

Fig. 7. Summary of the feasibility analysis of blockchain and IoT in agricultural food supply chains.

6.1. Technical feasibility

Several studies stand out for their high technical feasibility in the realm of blockchain technology applied to food traceability, each leveraging unique aspects of blockchain platforms and infrastructural support to achieve scalability and efficiency.

[40] utilizes Hyperledger Fabric, notable for its scalability, primarily attributed to the use of Raft, a Crash Fault Tolerant (CFT) consensus mechanism. The architectural design of Fabric, comprising various Docker containers, is deployed on an Alibaba Elastic Cloud Server (ECS). This strategic choice enhances scalability and performance, offering robust container management that supports Docker containers. The geographical distribution of ECS, akin to services like Amazon EC2, ensures optimized latency and high redundancy, making this approach technically feasible for widespread application.

Similarly [41], demonstrates high technical feasibility with their system built on the IOTA platform. Noteworthy for its data handling efficiency, IOTA's architecture was prototyped to emphasize scalability, making it a strong candidate for blockchain applications in food traceability that require rapid and large-scale data management.

Further enhancing technical feasibility [32], adopts the Algorand blockchain platform, known for its Pure Proof-of-Stake consensus algorithm. This choice is significant due to its minimal processing power requirement, crucial for scalability and supporting large-scale applications while ensuring environmental sustainability through low energy consumption.

[42] also utilizes Hyperledger Fabric, reinforcing the trend of selecting technically robust platforms. Like [40], the choice of Fabric

contributes to scalability and efficiency due to its permissioned nature and the use of Raft consensus. The dependency on cloud services, such as AWS blockchain manager, further underscores the technical feasibility of this approach, providing a stable and scalable foundation for the blockchain system and ensuring its applicability and reliability in diverse settings.

Adding to this landscape [38,39], and [37] also demonstrate high technical feasibility. These studies highlight the use of advanced blockchain and IoT technologies tailored to meet specific challenges in the agricultural sector. They utilize scalable and efficient blockchain architectures and IoT integration to enhance data integrity and streamline operations, setting new benchmarks in the field of food traceability.

Collectively, these studies underscore the importance of selecting appropriate blockchain platforms and supporting infrastructure to enhance technical feasibility in food traceability applications. By leveraging the unique strengths of platforms like Fabric, IOTA, and Algorand, along with robust IoT integrations, these studies establish a framework for developing scalable, efficient, and technically feasible blockchain solutions in the food industry.

6.1.1. Moderate

In analyzing the technical feasibility of blockchain applications in food traceability, three studies demonstrate moderate feasibility, each navigating the challenges and opportunities presented by their chosen technologies.

[29] utilizes Ethereum, a platform known for its robust smart contract capabilities but also recognized for its scalability limitations, particularly in transaction throughput. To mitigate these challenges, their approach incorporates off-chain storage platforms like IPFS (Inter- Planetary File System), which plays a crucial role in enhancing scalability. IPFS addresses the issue of large file storage in transactions, a significant concern in blockchain applications dealing with extensive data. However, despite this integration, the inherent scalability challenges of Ethereum remain a limiting factor. Additionally, the project benefits from existing cloud computing resources and software tools like React and JavaScript, enhancing its feasibility. The use of hardware tools such as Raspberry Pi and RFID/NFC tools in their implementation further contributes to the system's moderate technical feasibility.

Similarly [36], presents a system fully integrated into Ethereum, grappling with similar scalability issues. To enhance their model's efficiency, they incorporate MongoDB, a NoSQL database known for faster query execution, which is particularly beneficial in blockchain environments where data retrieval speed is crucial. Moreover, the use of MQTT, an efficient messaging protocol, helps optimize communication in constrained or challenging network conditions. This thoughtful integration of complementary technologies alongside Ethereum indicates a strategic approach to overcoming Ethereum's limitations, resulting in a moderate level of technical feasibility for their system.

Adding to these [18], also exhibits moderate technical feasibility. This study explores the use of a lightweight blockchain solution tailored for the olive oil industry, facing integration challenges with traditional agricultural practices despite its innovative approach. The specific use of blockchain to enhance product traceability within a niche market like olive oil highlights the need for customized solutions that address both technological capabilities and practical integration challenges.

Collectively, these studies highlight a common theme in the evolving landscape of blockchain applications: the need to balance the strengths of blockchain platforms like Ethereum with their inherent limitations, particularly in scalability. By integrating additional technologies such as off-chain storage solutions and efficient database systems, these studies demonstrate a path forward in enhancing the technical feasibility of blockchain-based systems in food traceability.

6.1.2. Low

In the broader context of blockchain applications for food traceability [35,43], and [33] present cases with varying degrees of technical feasibility challenges, primarily centered around the scalability of the blockchain systems they propose.

[35] face limitations in technical feasibility, primarily due to their system's reliance on Ethereum, which, while robust in its smart contract capabilities, is known for scalability challenges. Their approach, which considers small-scale food enterprises, suggests that a permissioned blockchain might have been more suitable to meet scalability needs. However, the prototype's foundation in Ethereum limits its scalability, rendering the system less technically feasible, especially for applications requiring high transaction throughput or large-scale data management.

[43] encounter a more significant feasibility challenge. Their system, fully built on and integrated into Ethereum, lacks mechanisms or strategies to address the well-known scalability limitations of the platform. The absence of scalability options in their model results in very low technical feasibility, as the system might struggle to manage the demands of a large-scale, high-throughput food traceability application without compromising performance.

[33] present a system with very low technical feasibility, largely due to its reliance on a GitHub repository that replicates MySQL with blockchain using a Proof of Work consensus. This approach raises substantial scalability concerns, as Proof of Work is resource-intensive and typically not suited for applications requiring rapid processing and high scalability. OurSQL, which lacks performance metrics and significant community support (evidenced by limited contributions and maintenance updates), further exacerbates these concerns. The system's design does not provide assurance that it can handle the complexities of a large-scale Food Traceability System (FTS), posing significant challenges for its practical implementation.

These cases exemplify the importance of choosing appropriate blockchain platforms and architectures in food traceability applications. While blockchain offers transformative potential for enhancing food safety and traceability, the selection of platforms and the design of the system are pivotal in determining the technical feasibility and practical applicability of these solutions. The challenges faced by Refs. [35,43], and [33] underscore the necessity of addressing scalability and performance in the initial design phase to develop effective and feasible blockchain-based food traceability systems.

6.2. Economic feasibility

6.2.1. High

In assessing the economic feasibility of blockchain applications for food traceability, the studies by Refs. [33,35,40], and [32] demonstrate high feasibility, each leveraging cost-effective technologies and strategies tailored to small and medium enterprises (SMEs) to achieve high economic feasibility through the use of cost-effective technologies like Zigbee protocol and Alibaba Elastic Cloud Server (ECS). Zigbee's low-cost, low-power requirements make it ideal for Machine-to-Machine (M2M) and Internet of Things (IoT) networks, particularly in applications where low data rates and power efficiency are crucial. The economic efficiency of ECS, with its pay-per-use model, further enhances the system's affordability. This approach not only ensures cost-effective data transmission but also aligns with customer satisfaction goals by providing effective traceability at a manageable cost.

[35] focuses on designing a system with SMEs in mind, considering the cost constraints faced by small-scale and medium-scale food enterprises. By incorporating technologies like BSON for data storage and RFID for tracking, coupled with efficient on and off-chain data management, they create an economically viable solution for SMEs. This approach significantly reduces the financial burden of implementing traceability systems, making them more accessible to smaller enterprises.

[33], while not explicitly focusing on a low-cost approach, still presents an economically feasible model for SMEs. The choice of affordable sensors and using OurSQL, a public repository with a GPL-3.0 license, make their system economically viable. The open-source nature of OurSQL, allowing for modification, distribution, and commercial use, offers SMEs a cost-effective solution for adopting blockchain-based traceability.

Lastly [32], capitalizes on the open-source aspect of the Algorand platform to enhance economic feasibility. Algorand's wide range of community and organizational repositories across various programming languages (Perl, Go, JavaScript, Python, C, etc.) offers SMEs a free, accessible foundation to build their traceability systems. This open-source approach, coupled with Algorand's technical advantages, makes it a financially viable option for SMEs looking to implement blockchain solutions.

Together, these studies demonstrate a shared commitment to making blockchain technology accessible and affordable for SMEs in the food industry. By strategically choosing cost-effective technologies and platforms, and focusing on the unique economic needs of smaller enterprises, these studies pave the way for broader adoption and implementation of blockchain-based food traceability systems, highlighting their potential to deliver effective solutions within a manageable budget.

6.2.2. Moderate and low

In evaluating the economic feasibility of blockchain applications in food traceability, several studies navigate different cost factors associated with their respective implementations, demonstrating a moderate level of feasibility.

[29] achieves a balance in economic feasibility through their implementation choices. While Ethereum's gas fees and transaction storage costs can be substantial, their decision to use IPFS for off-chain storage mitigates some of these expenses, particularly in terms of storage. The ABCDE approach they adopt for developing their decentralized application (DApp) incorporates agile practices, which can be cost-effective. However, their acknowledgment of the need to further research gas fees and the costs of newly designed RFID and NFC tools indicates that the economic feasibility is only partially achieved.

[36] presents a scenario with mixed economic implications. While their focus on low-cost sensors enhances feasibility, the setup costs for Ethereum Virtual Machines (EVMs) in each farm could be prohibitively high, especially for a large-scale system. The lack of detailed minimum hardware specifications and a cost analysis leaves the economic feasibility of their system in a moderate zone, especially when considering the implementation in a real-world agricultural setting.

[42] faces a similar situation of moderate economic feasibility. Although their use of the open-source Hyperledger Fabric platform initially suggests cost-effectiveness, their reliance on the AWS version of Fabric introduces additional costs. This factor could potentially make the solution less economically feasible for SMEs, especially those with limited budgets.

In contrast, the studies by Refs. [41,43] leave an economic feasibility gap in their research. Without explicit consideration of the costs associated with their blockchain solutions, it's challenging to assess their economic viability, particularly for SMEs. This omission highlights the importance of considering all aspects of feasibility, including economic, when developing blockchain solutions for food traceability.

Adding to these, studies such as [37,39] reflect moderate economic feasibility, balancing the costs of technology implementation with potential long-term benefits in operational efficiency and product traceability. These studies highlight the challenges and strategies involved in integrating advanced technologies into the food supply chain while managing costs effectively, ensuring that the technological innovations are accessible and beneficial to a broader range of stakeholders within the agricultural sector.

6.3. Legal feasibility

6.3.1. High

In assessing the legal feasibility of blockchain applications in food traceability, the studies by Refs. [29,40], and [35] stand out for their high legal feasibility. Each of these studies demonstrates a keen awareness of regulatory compliance, integrating principles and frameworks that align with existing legal standards in the food industry.

[29,40] both exhibit high legal feasibility through their close alignment with Hazard Analysis and Critical Control Points (HACCP) principles. HACCP is a systematic preventive approach to food safety widely recognized and adopted in the food industry for managing health risks. By modeling their solutions in accordance with HACCP principles, both studies ensure that their blockchain applications are not only technologically sound but also compliant with critical food safety regulations. This alignment is crucial in food

traceability, where adherence to safety standards is paramount.

Similarly [35], achieves high legal feasibility by modeling their system with the Electronic Product Code Information Services (EPCIS) framework. EPCIS is a standard for sharing information about the physical movement and status of products as they travel throughout the supply chain. By incorporating this framework, Lin et al. ensure that their solution adheres to established standards for product traceability. Moreover, the inclusion of regulators as part of the supply chain actors in their system demonstrates a proactive approach to ensuring legal compliance, recognizing the importance of regulatory oversight in the food supply chain.

In contrast, the other studies in this review do not explicitly address legal feasibility in their research. This omission highlights a potential gap in the comprehensive evaluation of blockchain solutions in food traceability, as legal compliance is a critical aspect that influences the viability and acceptability of such systems. The absence of a legal feasibility assessment in these studies suggests a need for further research or consideration to ensure that innovative blockchain applications can be effectively integrated into the highly regulated food industry.

Overall, the high legal feasibility of the solutions proposed by Fan et al., Cocco et al., and Lin et al. underscores the importance of aligning technological innovations with existing regulatory frameworks. Such alignment not only enhances the credibility and reliability of these solutions but also facilitates their smoother adoption and implementation in the food industry, ensuring that they meet both technological and legal requirements.

6.4. *Operational feasibility*

6.4.1. *High*

In the context of operational feasibility for blockchain applications in food traceability, the studies by Refs. [40,41], and [42] demonstrate high operational feasibility, each incorporating features that enhance the user experience and system functionality.

[40] achieve high operational feasibility through the integration of Hyperledger Explorer into their system. This integration allows users to easily check the status of the Fabric blockchain network, a feature that significantly enhances user confidence and satisfaction. By providing transparency and real-time insight into the blockchain's operation, the system becomes more user-friendly and trustworthy for organizations within the supply chain. This level of transparency and ease of use is particularly crucial in developing countries, where technological adoption may face more barriers. The perceived value from both customer and supply chain actor satisfaction plays a pivotal role in the system's potential for successful operationalization.

Similarly [41], presents a system characterized by fast response times, high throughput, scalability, and data efficiency. These technical attributes directly contribute to its operational feasibility. A system that responds quickly can handle large volumes of data efficiently, and scales effectively is more likely to be embraced by users, including supply chain actors and consumers. The performance and reliability of the system encourage user engagement and trust, which are essential for the operational success of any technological solution in the supply chain.

[42] further enhances operational feasibility by providing Small and Medium Enterprises (SMEs) with the ability to build permissioned blockchain solutions tailored to their specific enterprise use cases. The scalability of Hyperledger Fabric (HLF) in this context is a significant advantage, offering flexibility and customization to meet diverse enterprise needs. This adaptability, coupled with the perceived value from an end-user perspective, positions their system as an attractive option for SMEs looking to implement blockchain technology.

Collectively, these studies highlight the importance of user-centric features and system capabilities in determining the operational feasibility of blockchain solutions in food traceability. By focusing on aspects such as system transparency, responsiveness, scalability, and customization, these studies demonstrate a clear understanding of the practical requirements for the successful implementation and adoption of blockchain technology in the food industry. Their approaches underscore the significance of designing systems that not only meet technical and regulatory standards but also align with the needs and expectations of end-users, facilitating easier integration and operation in real-world supply chain environments.

6.4.2. *Moderate and low*

The operational feasibility of blockchain applications in food traceability, as assessed in the studies by Refs. [29,35,36], and [32], varies, reflecting differing degrees of system maturity and user-oriented considerations.

[29] exhibits moderate operational feasibility. Their approach, utilizing Ethereum and IPFS platforms along with the ABCDE development approach, is operationally feasible in developing countries. However, the study does not adequately address the economic implications of Ethereum's gas fees. This omission leaves a gap in the operational assessment, particularly concerning the cost efficiency of running the system. Hence, while the technical aspects are covered, the economic considerations, particularly the real money cost of operating the system, remain partially unexplored, leading to a classification of partial operational feasibility.

[35] also demonstrates moderate operational feasibility. Their system design caters to small and medium-scale food enterprises and is capable of handling large volumes of trace-ability information. However, the lack of user interface details or features that could enhance consumer confidence limits the system's appeal. The operational feasibility is therefore seen as moderate, considering that user engagement and confidence are crucial for the adoption and success of such systems.

[36] presents a system with a web interface (UI), indicating an effort to enhance user interaction and operational usability. However, the requirement for each farm to configure an Ethereum Virtual Machine (EVM) to Wireless Sensor Network (WSN) poses operational challenges. This requirement could be a significant barrier, especially in settings with limited technical expertise or resources, thus leading to a classification of moderate operational feasibility.

[32] faces low operational feasibility due to the public nature of the Algorand blockchain platform they utilize. While Algorand's

scalability is a strong point, its public structure, allowing universal access and participation in the consensus, is not typically suited for enterprise solutions that often require controlled access to information. SMEs might be hesitant to adopt a system that does not offer sufficient data privacy or access control. Consequently, despite its technical capabilities, the lack of incentives for SMEs to adopt this system due to privacy and control concerns leads to low operational feasibility.

In summary, while each of these studies offers promising blockchain solutions for food traceability, their operational feasibility varies based on how well they address end-user needs, system costs, and specific requirements of the food enterprise sector. The success of such systems in practical settings depends not only on their technical prowess but also on their ability to meet the economic and usability expectations of their intended users.

7. Open issues and future directions

The exploration of blockchain and IoT technologies in food traceability systems has underscored several critical open issues, necessitating focused attention in future research and development. These challenges are pivotal in shaping the operational efficacy and user adaptability of these technologies in the agricultural-food supply chain.

7.1. Enhancing network topology flexibility and deployment

In the context of African food supply chains, the rigidity of network topology in blockchain technology presents a critical challenge, particularly when system modifications necessitate changes in Docker compose files. This issue is exacerbated by the unique complexities and dynamic nature of African food supply chains, where rapid adjustments and scalability are often required to meet diverse regional demands. The current system's tendency to experience downtime during such reconfiguration is a significant barrier, impeding the effectiveness of blockchain in tracking and ensuring food safety across the continent.

Future research in this area should prioritize the development of dynamic network topologies tailored to the unique needs of African food supply chains. These advanced topologies would ideally be capable of adapting seamlessly to changes in the network configuration, which is crucial for a continent with diverse agricultural practices and supply chain structures. This adaptability is key to maintaining continuous operation and is crucial for real-time traceability in the food sector. Research could explore integrating advanced software-defined networking (SDN) solutions or container orchestration platforms like Kubernetes, which offer more flexibility and automation, aligning well with the diverse and fast-changing African food supply landscape.

Moreover, simplifying the deployment process of blockchain platforms like Hyperledger Fabric is essential, especially considering the varying levels of technological infrastructure and expertise across African countries. The current reliance on Linux shell scripts poses a significant challenge in regions where such technical skills might be scarce. Developing user-friendly interfaces, such as Graphical User Interfaces (GUIs), would make blockchain deployment more accessible to a broader range of users, including those with limited technical backgrounds. Additionally, higher-level automation scripts could streamline the deployment and management of blockchain networks, enhancing efficiency and reducing the potential for errors. Such advancements would be particularly beneficial in African contexts, where resources might be limited and ease of use can significantly impact the adoption and success of new technologies. Addressing these challenges is crucial for the successful implementation of blockchain technology in African food supply chains. By focusing on creating more adaptable and user-friendly blockchain network solutions, future research can play a pivotal role in enhancing food safety and traceability across the continent, supporting a more resilient and efficient agricultural sector.

7.2. Optimizing data uploading speed and consensus algorithms

In African food supply chains, the issue of data upload speed to the blockchain is particularly critical due to the consensus algorithm, which often serves as a bottleneck. This challenge is magnified in the African context, where the supply chain can involve a vast range of products, from locally grown produce to imported goods, each with its own set of data requirements. The diversity and volume of data in these supply chains necessitate an efficient and rapid uploading process to ensure timely and accurate traceability.

Future research and development efforts in this area should be particularly focused on tailoring or optimizing consensus algorithms for the unique demands of large-volume data handling typical in African food supply chains. These algorithms need to be robust enough to handle a high throughput of transactions, which is crucial for a continent that is rapidly expanding its agricultural and food market presence both locally and globally. An optimized consensus algorithm can significantly enhance the speed and efficiency of data uploading, making blockchain technology more viable and effective for real-time tracking and management in these diverse and often complex supply chains.

Additionally, implementing strategic data management approaches, such as information clipping, can be particularly beneficial in the African context. This approach involves setting parameters to limit the lifespan of data on perishable items, which is a significant segment of African agricultural produce. By automatically expiring data on perishable goods after a certain period, the system can prevent unnecessary data accumulation, maintain optimal performance, and reduce storage costs. This method is especially relevant for perishable agri-cultural products that are a staple in many African countries, ensuring that the blockchain system remains efficient and not overloaded with redundant data.

These innovations are crucial for the adaptation of blockchain technology in African food supply chains. By addressing the specific challenges of data upload speed and management in these diverse and dynamic supply networks, blockchain technology can be more effectively leveraged to enhance the transparency, safety, and efficiency of food distribution across the continent, supporting the growth and sustainability of the African agricultural sector.

7.3. Balancing public blockchain accessibility and privacy concerns

The accessibility and transparency of public blockchains, while beneficial for traceability, present significant privacy and data security challenges within African food supply chains. In a continent where the agricultural sector is not only a major economic driver but also a vital component of daily sustenance, the need for a balanced approach to blockchain technology is paramount. Public blockchains offer the advantage of transparent and accessible records, essential for verifying the authenticity and origin of food products. However, this openness can potentially expose sensitive supply chain data, posing risks to both businesses and consumers.

Future research and development in this area should concentrate on creating blockchain models that harmoniously balance public accessibility with the need for private confidentiality, a crucial aspect in the diverse and often informal markets across Africa. Hybrid blockchain architectures, which combine elements of both public and private blockchains, could be particularly effective in African contexts. These architectures would allow for the transparency needed to ensure food traceability and safety while maintaining the privacy necessary for protecting sensitive supply chain information.

Moreover, enhanced permissioned blockchain systems offer another promising solution. These systems provide stricter access controls compared to public blockchains, allowing only authorized participants to access certain information. This approach could be highly beneficial in environments where information sensitivity is high, and data security is paramount.

Such permissioned systems could be tailored to meet the specific needs of different stake-holders in African food supply chains, from smallholder farmers to large distributors and retailers.

Developing these nuanced blockchain solutions requires a deep understanding of the unique challenges and needs of African food supply chains. Research should focus not only on the technological aspects but also consider the socio-economic and cultural context of food production and distribution in Africa. By doing so, future blockchain models can be more effectively designed to support the secure, transparent, and efficient movement of food products across the continent, thereby enhancing food security and bolstering the resilience of African agricultural systems.

7.4. Complex food supply chain networks and model robustness

In addressing the current landscape of blockchain models for food supply chains, it's evident that many of these models are tailored to relatively straightforward networks. This simplicity, while useful for basic understanding and initial applications, does not fully capture the intricate realities of real-world food supply chains, particularly in diverse and multifaceted environments like those found across the African continent. To bridge this gap, future research must focus on extending and refining these blockchain models to accommodate more complex and nuanced supply chain networks. Such research would significantly contribute to evaluating the robustness and scalability of blockchain solutions under various real-world conditions.

Pilot studies, conducted in complex and realistic supply chain scenarios, are essential to gain a deeper understanding of the practical challenges and limitations inherent in cur-rent blockchain models. These studies would provide critical insights into how blockchain technology performs in dynamic, multifaceted supply chain environments, revealing areas where improvements are necessary. By testing these models in intricate settings that mirror the complexities of real-world operations, researchers can identify and address specific issues related to system scalability, data integrity, and user interaction.

The resolution of these open issues is a pivotal step towards the advancement and successful implementation of blockchain and IoT technologies in food traceability systems. Future research efforts should be directed towards enhancing the adaptability, efficiency, and user-friendliness of these technologies. By doing so, we can ensure their effectiveness in bolstering food safety and transparency across the agricultural-food sector. Such improvements are not only crucial for the technological evolution of food traceability systems but also for build-ing stronger, more resilient, and transparent food supply chains that can meet the evolving demands and challenges of the global food industry.

7.5. Adoption of blockchain as a service (BaaS) for Enhanced Traceability

To further streamline the adoption of blockchain technology in African agricultural supply chains, using Blockchain as a Service (BaaS) platforms could be particularly advantageous. BaaS platforms offer a cloud-based solution to develop, host, and use blockchain applications without the complexities of managing and maintaining the underlying infrastructure. These platforms provide the necessary blockchain framework and infrastructure, enabling businesses and organizations to focus on the application aspect of the technology rather than on its operational intricacies.

The adoption of BaaS platforms can significantly reduce the entry barriers for implementing blockchain technology, especially for smallholder farmers and SMEs who may lack the technical expertise and financial resources to develop blockchain systems in-house. By leveraging BaaS, these stakeholders can access sophisticated blockchain solutions through a subscription-based model that is scalable, cost-effective, and less resource-intensive.

Moreover, BaaS platforms are designed to ensure high levels of security and privacy, offering customizable permission settings that can accommodate the specific privacy needs of different stakeholders within the food supply chain. This feature is crucial in managing the transparency-privacy balance, ensuring that sensitive data is protected while maintaining the traceability and accountability that blockchain offers.

By incorporating BaaS into the blockchain adoption strategy for African food sup-ply chains, future research can explore more accessible, efficient, and scalable models for blockchain implementation. This approach not only enhances the robustness of food traceability systems but also supports the broader integration of blockchain technology across diverse agricultural settings in Africa, thereby contributing to the overall resilience and efficiency of the sector.

8. Conclusions

This review meticulously evaluates the role of blockchain and Internet of Things (IoT) technologies in transforming African agricultural food supply chains. It underscores the significant potential of these technologies to revolutionize food traceability, addressing critical challenges of food safety, traceability, and supply chain efficiency. However, the adoption of these technologies in Africa is not without its complexities, including issues related to scalability, cost-efficiency, regulatory compliance, and seamless integration with existing systems. The paper emphasizes the importance of a nuanced approach, one that is cognizant of the diverse economic, infrastructural, and regulatory environments across African nations. As blockchain and IoT technologies continue to evolve, they are anticipated to become integral in enhancing food safety and supply chain efficiency throughout the continent. This evolution, however, necessitates a concerted collaborative effort from governments, industry stakeholders, and technology providers. Together, they must navigate and overcome the prevailing challenges to fully leverage the potential of these innovative technologies.

In conclusion, the future trajectory of food traceability in Africa hinges on the effective implementation and scaling of blockchain and IoT technologies. This represents a dynamic and promising area of innovation and growth in the agricultural sector. The successful integration of these technologies into African food supply chains could set a precedent for global food safety and traceability, marking a significant stride in agricultural advancement and food security.

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Data availability

No data was used for the research described in the article.

CRediT authorship contribution statement

Andrews Tang: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Eric Tutu Tchao:** Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Andrew Selasi Agbemenu:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Eliel Keelson:** Writing – review & editing, Visualization, Validation, Formal analysis, Conceptualization. **Griffith Selorm Klogo:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Jerry John Kponyo:** Writing – review & editing, Visualization, Validation, Supervision, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Eric Tutu Tchao reports financial support was provided by Carnegie Corporation of New York. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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