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A Systematic TOGAF-Driven Framework for Blockchain-Based Food Traceability with Access Control Lists

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Abstract

The global food supply chain involves multiple stakeholders, including farmers, manufacturers, distributors, retailers, and consumers, requiring a robust traceability system to ensure food security, transparency, and consumer trust. However, existing systems face significant challenges, such as limited transparency, data tampering risks, and inefficient access control mechanisms, leading to supply chain inefficiencies and regulatory concerns. This framework paper develops a systematic model that integrates The Open Group Architecture Framework (TOGAF), blockchain technology, and Access Control Lists (ACLs) to address these limitations. The TOGAF Architecture Development Method (ADM) is applied to design and implement the framework, focusing on business architecture, data security, and stakeholder collaboration. The framework ensures data immutability, privacy, and secure access control while enhancing scalability and adaptability across diverse supply chains. By integrating these technologies, the proposed framework is expected to enhance traceability, strengthen data security, and improve stakeholder engagement, making food supply chains more reliable and transparent for regulators and consumers. The novelty of this framework lies in its unique integration of TOGAF-driven enterprise architecture, blockchain, and ACLs, creating a privacy-preserving, tamper-proof food traceability system. This integration enhances industry practices and provides a scalable, sustainable solution, contributing to global food security and consumer trust.

Keywords: Blockchain; Food Traceability; Access Control Lists; TOGAF; Supply Chain Transparency; Food Security.

1. Introduction

Agriculture is fundamental to national security and global sustenance, providing essential nutrition and energy worldwide. Many nations prioritize food security, recognizing its importance over other industries such as manufacturing [1]. However, unlike manufacturing, agriculture is highly dependent on natural variables such as land,

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climate, and seasonal labour, which hinder the widespread adoption of advanced technologies [2]. This technological lag has restricted the development of robust food traceability systems essential for ensuring food safety, improving transparency, and fostering consumer trust. An effective traceability system benefits all stakeholders across the supply chain [3, 4], as illustrated in Figure 1.

Figure 1. Traditional Food Supply Chain Management

Food traceability plays a critical role in crisis management and regulatory compliance. During the 2006 E. coli outbreak in North America, an effective traceability system delayed identifying the contamination source, leading to significant economic losses and reduced public trust [5, 6]. Similarly, in 2011, a food fraud incident in China, where fox meat was mislabeled as donkey meat, exposed serious vulnerabilities in traditional food supply chains [7]. These cases highlight the urgent need for efficient and transparent food traceability mechanisms to enhance responsiveness and risk mitigation.

Despite its significance, current food traceability solutions have several limitations. Traditional technologies such as RFID, sensor networks, and data mining rely on centralized storage, making them vulnerable to data manipulation, errors, and limited visibility into food product origins [8-10]. Blockchain has emerged as a promising alternative due to its decentralized, immutable, and transparent nature [11]. Its cryptographic safeguards and distributed ledger design address key supply chain trust and transparency challenges [12]. However, blockchain adoption also introduces privacy concerns, as many implementations grant unrestricted access to sensitive data, raising confidentiality risks [13-15].

This study proposes a novel framework integrating blockchain with Access Control Lists (ACLs) to address these challenges and enable privacy-preserving data access. ACLs define granular user permissions, ensuring only authorized stakeholders can access specific data while maintaining transparency where necessary [16]. Previous studies have explored blockchain-ACL integration, but their scope is limited. For instance, ChainSCAN primarily focuses on activity monitoring without offering a holistic traceability solution [17], while other frameworks are tailored to specific sectors, such as aquaculture and lack broader agricultural applications [18].

A study by Liu et al. [19] integrated The Open Group Architecture Framework (TOGAF) with permissioned blockchain technology for food traceability. However, it does not emphasize scalability, a critical factor for implementing dynamic and evolving food supply chains. Addressing these limitations, our study develops a TOGAF-driven blockchain-based food traceability framework with ACL integration, ensuring a systematic, scalable, and privacy-preserving approach.

This study introduces a novel TOGAF-driven blockchain-based food traceability framework with ACL integration, ensuring systematic, scalable, and privacy-preserving implementation. TOGAF provides a structured methodology for aligning business objectives with technological solutions, facilitating effective deployment in agricultural supply chains [20]. The framework follows TOGAF's Architecture Development Method (ADM), encompassing Business Architecture, Information Systems Architecture, and Technology Architecture, to systematically address technical and operational challenges [21].

By leveraging TOGAF's structured principles alongside blockchain and ACL technologies, the proposed framework enhances data privacy, transparency, and scalability in food traceability systems. Beyond reinforcing trust and food security, this research provides valuable insights for developing resilient, technology-driven supply chains in the agricultural sector.

The rest of the paper is organized as follows: Section 2 reviews related works, identifying gaps in existing research. Section 3 details the proposed framework, including its architecture, implementation, and contributions to food traceability. Finally, Section 4 concludes the paper, summarizing key findings and suggesting directions for future research.

2. Literature Reviews

The increasing demand for safe, sustainable, high-quality food products has intensified the need for robust traceability systems in agri-food supply chains. These systems ensure food integrity and help stakeholders meet growing transparency, accountability, and risk mitigation expectations. This section synthesizes current research on food traceability systems, blockchain technology, and TOGAF as a structured enterprise architecture framework. It identifies key gaps in existing approaches and establishes the necessity for a novel framework integrating blockchain with TOGAF to achieve secure, scalable, and efficient food information management. Insights from related domains, such as healthcare and AI-driven methodologies, provide valuable perspectives on how structured solutions can enhance traceability and data governance.

2.1. Food Traceability: Challenges and Opportunities

Achieving higher consumer trust and supply chain sustainability requires enhanced traceability systems to track and authenticate food products throughout their lifecycle. Identifying contamination sources is crucial for preventing foodborne illnesses, reducing waste, and improving supply chain efficiency. However, traditional traceability systems remain fragmented, often lacking real-time tracking capabilities and transparent verification mechanisms.

Several technologies—RFID, Wireless Sensor Networks (WSN), QR codes, NFC, and IoT-enabled devices—have been deployed to enhance food traceability [22]. While these technologies enable real-time monitoring, they rely on centralized databases, making them vulnerable to data tampering, manipulation, and security breaches [23]. Moreover, consumers often struggle to access complete transaction histories, reducing their ability to verify the origin and safety of food products [24].

Robust agri-food information management systems are essential for ensuring traceability, security, and transparency. However, current solutions fail to build sufficient stakeholder trust, as highlighted in Hassan et al. [25] study. Traditional traceability frameworks often lack the resilience to withstand disruptions in global agri-food supply chains [26]. Addressing these gaps necessitates the integration of privacy-preserving, tamper-proof technologies that ensure data integrity and consumer confidence.

Frameworks such as the ubiquitous Personal Health Record (uPHR) [27], initially developed for managing sensitive health data, demonstrate the value of systematic data security and access control approaches. Applying similar methodologies in agriculture could enhance traceability by balancing centralized and decentralized models, fostering greater stakeholder trust.

Emerging technologies such as Artificial Intelligence (AI) and Machine Learning (ML) present additional opportunities for improving food traceability. For instance, AI-driven contamination detection models analyze real-time data to predict food safety risks [28]. Similarly, ML algorithms can forecast supply chain disruptions, optimize decision-making, and mitigate risks before they escalate. Studies such as Patel & Gupta [29] have demonstrated how AI-based models predict food safety risks using historical and real-time data, enabling proactive interventions. Likewise, Kumar & Singh [30] highlighted how AI enhances supply chain efficiency by predicting demand fluctuations and identifying logistical bottlenecks. Additionally, a systematic review by Ellahi et al. [31] explored the integration of Near Field Communication (NFC) and blockchain technologies to create a more secure and efficient food supply chain, enhancing safety and transparency.

Despite these advancements, scaling these technologies remains challenging, primarily due to high implementation costs, lack of technical expertise, and resistance to change among stakeholders [32]. Overcoming these barriers requires standardized frameworks and collaborative efforts from governments, industry leaders, and technology providers to ensure widespread adoption.

2.2. Blockchain as the Solution

Blockchain technology has emerged as a transformative solution for addressing traceability challenges in agri-food systems. As a decentralized ledger, blockchain securely records transactions, or blocks, across a network of nodes, making it resistant to tampering and data breaches [33]. Its cryptographic safeguards ensure data integrity, while its immutability guarantees that it cannot be altered once a block is created [34]. These features, decentralization, transparency, security, and immutability, make blockchain an ideal choice for enhancing traceability in agri-food supply chains.

Integrating blockchain with advanced decision-making algorithms such as neural networks and ML further enhances its potential in agri-food traceability. Studies such as Anbananthen et al. [35] demonstrated how data mining techniques extract actionable insights from blockchain-registered datasets, enabling real-time fraud detection, risk assessment, and supply chain optimization. With AI-driven automation, blockchain can streamline quality assurance, contamination tracking, and regulatory compliance [36].

Several studies have proposed blockchain-based food traceability systems. For example, Iansiti & Lakhani [37] integrated blockchain with NFC to enable real-time product verification, improving supply chain transparency. Similarly, Johnson & Wright [38] developed a blockchain-enabled traceability framework for the wine industry, allowing stakeholders—from grape growers to consumers—to verify transaction data securely. These implementations demonstrate blockchain's effectiveness in enhancing transparency, ensuring data integrity, and fostering stakeholder trust. Sudarssan [39] presented a framework to strengthen trust and transparency in the food supply chain while ensuring food safety through blockchain technology. By leveraging decentralized ledger technology, the framework enhances traceability, minimizes fraud, and improves overall efficiency. These advancements demonstrate the growing significance of blockchain in modernizing food supply chain management.

Despite its potential, blockchain adoption in agri-food traceability faces several challenges, including high energy consumption, as public blockchains require extensive computational power, raising concerns about sustainability and cost-effectiveness [40]. Additionally, scalability limitations hinder blockchain architectures from handling high transaction volumes, restricting their applicability to large-scale supply chains. Another key issue is integration complexity, as many agri-food systems rely on legacy infrastructure, making blockchain adoption expensive and technically challenging. These challenges underscore the need for a structured implementation framework that aligns blockchain solutions with business objectives, scalability requirements, and operational feasibility. In this regard, TOGAF emerges as a critical enabler, providing a systematic approach to addressing these limitations and facilitating efficient, scalable, and cost-effective blockchain integration in food traceability.

2.3. The Role of TOGAF in Implementation

Implementing blockchain-based solutions requires a systematic enterprise architecture framework to align technological solutions with business objectives and operational requirements. TOGAF provides a structured methodology for designing, planning, and governing enterprise architectures [41]. Its ADM ensures that blockchain solutions are deployed scalable, secure, and strategically [42]. Figure 2 illustrates TOGAF's ADM framework, which includes key phases such as Preliminary, Architecture Vision, Business Architecture, Information Systems Architecture, and Technology Architecture. This study focuses on the initial five phases, establishing a solid foundation for blockchain-based food traceability implementation.

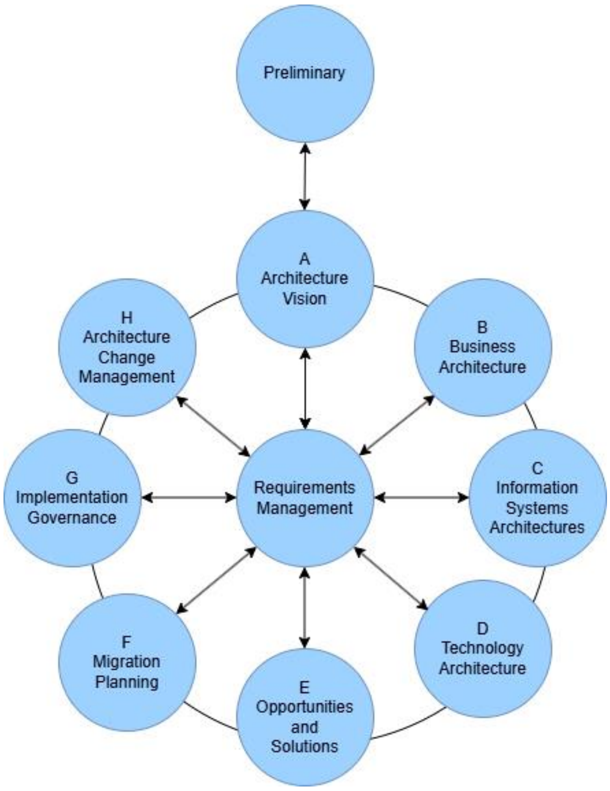

Figure 2. ADM of TOGAF by The Open Group

A targeted data gathering and validation approach is crucial for effectively applying TOGAF in blockchain-based systems. Tools such as focused web crawlers [43] play a vital role in collecting and verifying agri-food data. These crawlers can retrieve real-time information from diverse sources, ensuring the blockchain ledger is continuously updated with accurate and timely data. This capability enhances the proposed framework's transparency and reliability while addressing the inherent complexities of agri-food supply chains.

By applying TOGAF, this study addresses several critical challenges in food traceability, including:

- Interoperability: Ensuring seamless integration of blockchain with existing systems.
- Scalability: Facilitating the development of solutions capable of meeting evolving organizational needs.
- Risk Mitigation: Providing a structured methodology to identify and manage risks during implementation.
- Collaboration: Aligning IT and business stakeholders to optimize resource utilization and decision-making.

TOGAF's focus on standardization and interoperability makes it particularly suited to blockchain-based food traceability systems. Its tools, templates, and best practices enable organizations to navigate challenges across business, data, application, and technology domains [31, 44].

2.4. Literature Review Summary

The review of existing literature highlights the growing significance of food traceability systems in ensuring food safety, supply chain transparency, and consumer trust. Traditional traceability solutions, including RFID, NFC, and IoT-enabled tracking systems, have improved real-time monitoring but remain constrained by centralized architectures, data tampering risks, and scalability limitations. In contrast, blockchain technology has emerged as a transformative solution, offering decentralization, immutability, and enhanced security for food supply chains. However, challenges such as high energy consumption, limited scalability, and integration complexities continue to hinder its widespread adoption. Studies have explored AI-driven contamination detection models, machine learning-based supply chain optimization, and blockchain-enabled frameworks, demonstrating significant advancements in the field. Many of these solutions lack a structured implementation approach, leading to fragmented adoption and operational inefficiencies.

This study adopts a structured enterprise architecture approach using TOGAF to address these challenges. TOGAF provides a systematic and scalable methodology for integrating blockchain with existing food traceability systems while ensuring interoperability, privacy-preserving transparency, and risk mitigation. Unlike prior blockchain-based models focusing solely on data integrity and immutability, the proposed framework leverages TOGAF's ADM to ensure business alignment, governance, and seamless IT integration. By aligning blockchain technology with TOGAF principles, this study aims to provide a scalable, structured, and adaptable framework for modern food traceability systems.

3. Research Methodology

Building upon the insights from the literature review, this study proposes a framework for developing a blockchain-based food traceability system integrated with ACLs and guided by TOGAF. Rather than focusing on deep technical implementation, this methodology emphasizes the structured phases and principles of TOGAF, ensuring a systematic, scalable, and adaptable architecture for food traceability. The ADM within TOGAF is the core process, providing a structured and systematic approach to designing and implementing the proposed framework.

3.1. Preliminary Phase

The Preliminary Phase in TOGAF marks the initial step in the ADM lifecycle, laying the groundwork for a successful architecture development process. This phase focuses on defining the architectural vision, governance structures, and guiding principles to ensure alignment with business objectives and regulatory requirements. Key activities include identifying key stakeholders (Figure 3), defining architecture principles, and customizing the TOGAF framework to align with the organization's context and objectives. Identifying key stakeholders within the food traceability ecosystem ensures representation across all critical sectors, facilitating collaboration and regulatory compliance. Additionally, this phase involves establishing architecture principles that guide the design, implementation, and operation of the proposed blockchain-based traceability system, ensuring alignment with both business objectives and technological requirements. Furthermore, the TOGAF framework is customized to address the unique challenges of the agri-food supply chain, with a focus on data security, interoperability, and scalability, ensuring that the system remains resilient, efficient, and adaptable to evolving industry needs.

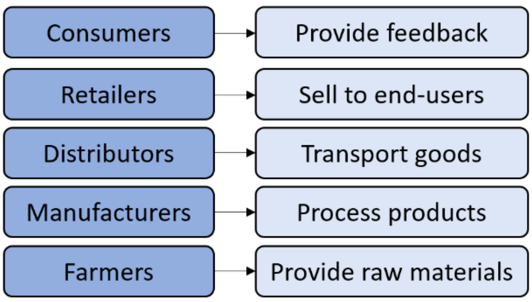

Figure 3. Stakeholder Ecosystem

These principles encompass the following domains:

- Business Architecture: Facilitates cross-sector collaboration, regulatory compliance, and stakeholder coordination.
- Data Architecture: Ensures data integrity, immutability, and privacy through blockchain and ACL-based access control.
- Application Architecture: Enables integration with IoT, blockchain, and AI tools for real-time data exchange and analytics.

- Technology Architecture: This focus is on scalability, fault tolerance, and real-time data capture for a resilient supply chain framework.

These principles, summarized in Table 1, address the unique challenges of food traceability in agriculture by providing a comprehensive foundation that integrates business, data, application, and technology architectures.

Having established the foundational principles, stakeholder roles, and governance structures in this Preliminary Phase, the next step focuses on defining the high-level architecture vision. This phase provides a strategic roadmap for addressing the limitations of existing food traceability systems by leveraging blockchain, ACLs, and TOGAF's structured approach. It sets the direction for system development, ensuring the proposed framework aligns with business objectives, regulatory requirements, and technological advancements.

Table 1. TOGAF-Aligned Principles for Food Traceability with Blockchain and ACL

Principle	Statement	Rationale	Implication
Business	The system must provide transparent and immutable traceability records for all authorized stakeholders.	Transparency fosters trust by ensuring that data cannot be altered or tampered with.	• Business processes must align with blockchain integration. • Training for stakeholders on system usage is essential.
	All stakeholders must be accountable for their traceability data contributions.	Enforcing accountability ensures accurate data entry and builds a reliable food supply chain.	• Policies for detecting and penalizing non-compliance must be established. • Clear roles and responsibilities for data verification are required.
Application	The system must utilize blockchain for decentralized data storage and seamless information sharing.	Decentralization enhances resilience, eliminates single points of failure, and fosters trust.	• Applications must support blockchain API integration. • Legacy systems may require updates or replacements.
	Access control mechanisms must enforce role-based permissions.	ACLs ensure only authorized users can access or modify data, enhancing security and privacy.	• ACLs must be regularly updated to reflect role changes. • Authentication and authorization systems must integrate with ACLs.
Data	The system must ensure data integrity through blockchain immutability.	Immutable data records guarantee accuracy and compliance and prevent tampering.	• Data must be structured and validated before being committed to the blockchain. • Mechanisms for correcting erroneous entries must be implemented.
	Sensitive data must be encrypted and access-controlled to comply with privacy laws.	Protecting sensitive data prevents misuse and ensures compliance with privacy regulations.	• Encryption standards must be enforced for sensitive data. • Blockchain and ACL designs must balance privacy with transparency.
Technology	The system must be scalable to handle growing transaction volumes and an increasing number of stakeholders.	As the food supply chain expands, the system must efficiently support more transactions and users.	• Cloud-based or modular infrastructure may be required. • Regular performance testing and scalability assessments are necessary.

3.2. Phase A: Architecture Vision

The Architecture Vision phase establishes the proposed framework's high-level goals and objectives while addressing the key limitations of existing food traceability systems. Current systems face significant challenges, including insufficient data privacy due to unrestricted stakeholder access, reliance on centralized data storage that is prone to tampering, and the lack of robust access control mechanisms such as ACLs.

The proposed framework integrates blockchain technology with ACLs to overcome these limitations, creating a privacy-preserving, tamper-proof traceability system. The framework leverages a consortium blockchain strategically chosen to enable collaborative transaction management and validation among key stakeholders, including producers, distributors, retailers, and regulatory bodies. By employing a consortium model, the system ensures that only authorized participants can access and record data, enhancing security and trust within the supply chain. Unlike public blockchains, which allow unrestricted access, a consortium blockchain ensures that only approved stakeholders participate in transaction validation, enhancing data privacy, security, and compliance while maintaining transparency within the food supply chain.

This approach balances decentralization and controlled access, ensuring that sensitive supply chain information remains protected while maintaining transparency and data integrity. Figure 4 illustrates the proposed architecture, which is structured into four key layers, each addressing specific functional and security requirements within the blockchain-based traceability system.

Business Layer

This layer represents the various stakeholders involved in the food supply chain, including farmers, manufacturers, distributors, retailers, and consumers. Each stakeholder interacts with the system to record, access, and verify traceability data relevant to their role, ensuring supply chain integrity and compliance.

IoT Traceability Layer

This layer captures and transmits traceability data specific to each stakeholder. Farmers record details like farm location, certifications, and harvest details, ensuring traceability from the point of origin. Manufacturers record processing information, batch IDs, and expiration dates, providing critical product safety and quality data. Distributors track transportation routes and storage conditions, ensuring proper handling and compliance with safety regulations. Retailers monitor sales and inventory data, facilitating efficient stock management and traceability. Consumers access detailed product journey information, enhancing transparency, trust, and informed purchasing decisions. It should be noted that the data captured in Figure 2 are just some examples; a comprehensive one will be discussed in the upcoming section.

Blockchain Layer

This layer is the system's core, where all traceability data is recorded in a secure, immutable, distributed ledger. Key transactions—harvesting, processing, and transportation—are stored as blocks in the blockchain. ACLs are enforced at this layer to regulate access based on stakeholder roles, ensuring only authorized entities can view or modify specific data. For instance, regulatory bodies and auditors may have read-only access to verify compliance, while manufacturers can update processing data but cannot modify farm-origin records. This ensures that sensitive data remains protected from unauthorized modifications while allowing relevant stakeholders to access essential information. Additionally, blockchain's immutable ledger preserves a transparent audit trail, enabling stakeholders to verify the history of food products without exposing confidential business information.

Application Layer

This layer is where the actual applications and user interfaces are built on the blockchain technology. It provides user interfaces and dashboards tailored for different stakeholders, enabling role-based access to data.

- Farmers: View and manage their farm data, track crop growth, and access market information.
- Manufacturers: Monitor production processes, manage inventory, and track product quality.
- Distributors: Track shipments, optimize logistics, and manage transportation routes.
- Retailers: Manage inventory, track sales, and provide consumers with product information.
- Consumers: Access product information, trace the origin of their food, and make informed purchasing decisions.

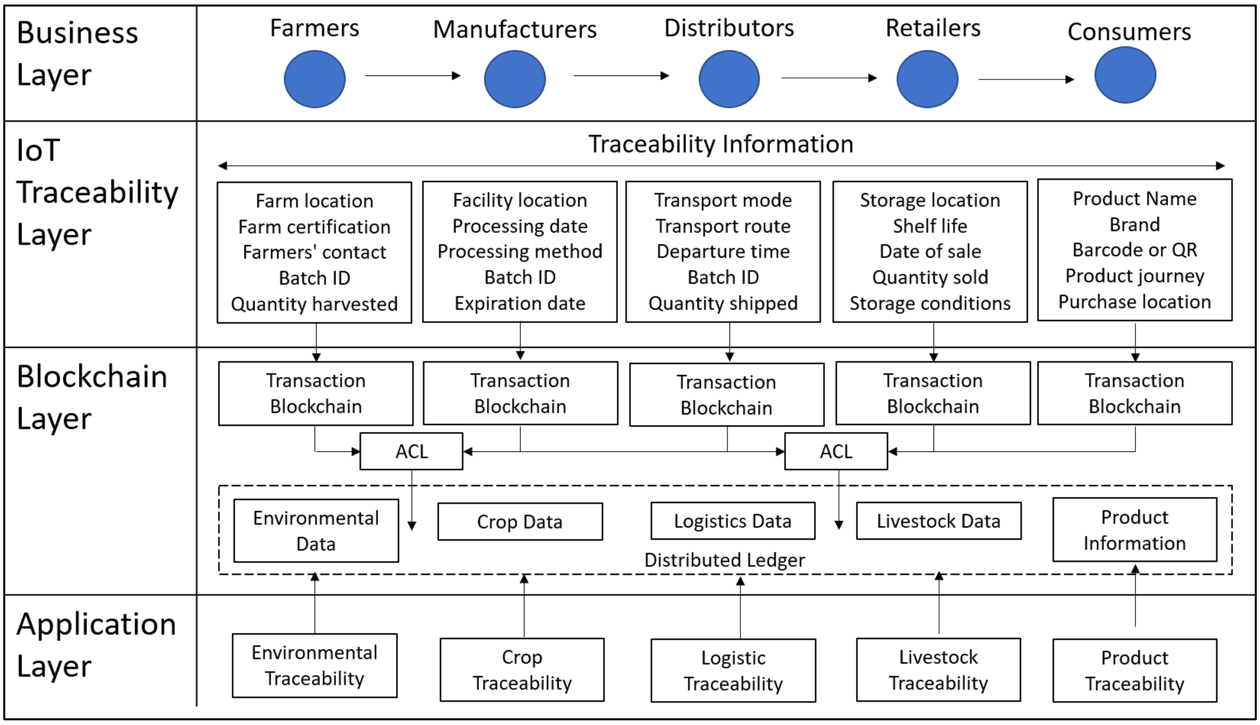

Figure 4. Architecture of Blockchain-ACL Food Traceability System

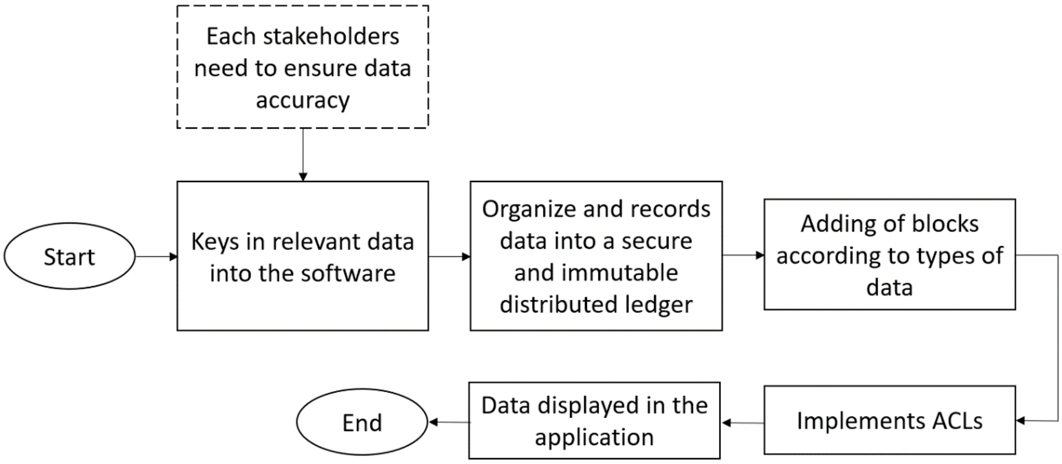

Figure 5. Process Vision on Our Proposed Approach

The process vision of the proposed framework, as illustrated in Figure 5, ensures ease of implementation and usability for all stakeholders within the food supply chain. The process begins with data collection, where stakeholders—including farmers, manufacturers, distributors, and retailers—gather and input relevant product information using mobile devices connected via Wi-Fi or cellular networks. This data includes farm locations, processing details, transportation routes, and storage conditions, ensuring comprehensive traceability from production to distribution.

Next, in the data recording phase, the collected information is securely structured and stored on the blockchain, leveraging its tamper-proof, secure, and transparent nature. Following this, the block addition phase organizes and records each event—such as harvesting, processing, and transportation—as an immutable block within the blockchain ledger. To uphold data privacy and security, ACLs) regulate access, ensuring only authorized entities can view, modify, or delete specific information.

Finally, the data display phase allows stakeholders to access relevant insights through a user-friendly application interface tailored to their roles. Farmers, manufacturers, distributors, retailers, and consumers interact with the system seamlessly, retrieving real-time traceability insights pertinent to their needs. This structured process vision ensures that the system remains comprehensive, transparent, and accessible, fostering trust, efficiency, and accountability across the entire food supply chain.

The key outputs of Phase A include a high-level design outlining the functionalities of the four layers, ensuring that each layer effectively fulfils its designated role. The proposed framework aligns stakeholders by addressing the needs of all supply chain participants while also supporting organizational objectives such as transparency, scalability, and security. This comprehensive architectural vision serves as a strategic roadmap, guiding the subsequent TOGAF ADM phases to facilitate the systematic implementation of the blockchain-based food traceability system.

Building on the high-level goals and architectural vision established in Phase A, the next phase, Phase B: Business Architecture, focuses on identifying the capabilities and processes required to realize the envisioned traceability framework.

3.3. Phase B: Business Architecture

The Business Architecture phase in TOGAF focuses on defining an organization's strategic goals, processes, and capabilities. It ensures that IT investments align with business objectives and foster innovation. This phase provides a comprehensive view of the business landscape, enabling organizations to integrate blockchain-based food traceability systems effectively.

In alignment with the Architecture Vision established in Phase A, Table 2 presents the business and IT capability assessments essential for implementing a blockchain-ACL-based food traceability solution. The evaluation begins with evaluating the current traceability state, analyzing data accuracy, information-sharing practices, and stakeholder collaboration. It then defines the desired future state, focusing on end-to-end traceability, real-time data access, and seamless data sharing across the supply chain. Additionally, evaluating IT infrastructure and operational processes identifies necessary upgrades and opportunities for efficiency improvements through blockchain integration, ensuring the system remains scalable, adaptable, and aligned with business objectives. By conducting these capability assessments, organizations can ensure that the blockchain-based traceability solution is aligned with business objectives, adaptable to future changes, and scalable for efficient operations.

Table 2. Business and IT Capability Assessments for Food Traceability using Blockchain-ACLs

Assessment	Description	TOGAF Principal Alignment
	Business Capability	
Capabilities of the Business	Evaluates the current level of traceability across the food supply chain, focusing on data accuracy, information-sharing practices, and stakeholder collaboration.	**Business Alignment:** Ensures the solution aligns with the organization's strategic goals and objectives.
Baseline State	Identifies existing traceability systems, data sources, and data collection and sharing processes. Analyzes data quality and identifies gaps in the information flow.	**Iterative Implementation:** Supports a phased approach, starting with a pilot project and expanding to the entire supply chain.
Future State Aspiration	It aims to achieve end-to-end traceability from farm to fork, with real-time access for authorized stakeholders and seamless, secure data sharing.	**Long-Term Vision:** Establishes a clear path toward a transparent, efficient, and resilient traceability system.
	IT Capability	
Baseline and Target Maturity of Change Processes	Assesses the organization's IT infrastructure (hardware, software, network connectivity, data security) and evaluates its readiness for blockchain adoption.	**Adaptability**: Ensures the solution can evolve with technological changes, regulations, and market demands.
Baseline and Target Maturity of Operational Processes	Analyzes business processes related to food handling, logistics, and quality control, identifying opportunities for improvement through blockchain integration.	Scalability: Supports a scalable system that accommodates growing data volumes and transactions.

Beyond technical implementation, the proposed framework ensures compliance with international food safety and traceability regulations through several key mechanisms. By integrating TOGAF with blockchain technology and ACLs, the system aligns business processes with global regulatory standards such as the Global Food Safety Initiative (GFSI), Hazard Analysis and Critical Control Points (HACCP), ISO 22000 (Food Safety Management Systems), and the Food Safety Modernization Act (FSMA). Blockchain's immutable ledger prevents data tampering, ensuring all transactions are verifiable and traceable for compliance audits. Additionally, role-based ACLs restrict data access to authorized stakeholders while maintaining controlled transparency, allowing regulatory bodies to conduct audits without exposing sensitive business information. TOGAF's structured methodology further strengthens compliance by providing a scalable and interoperable framework, ensuring that food traceability systems can adapt to evolving international regulations while maintaining transparency, accountability, and security. By incorporating these compliance mechanisms, the framework enhances trust, regulatory adherence, and operational efficiency across the global food supply chain.

3.4. Phase C: Information Systems Architecture

With the necessary business processes and capabilities established, the Information Systems Architecture phase in TOGAF focuses on designing applications and data structures that support business operations. This phase ensures the technology framework aligns with business objectives, enabling efficient data flow and interoperability across the food supply chain. In this phase, Table 3 outlines the key information requirements for each stakeholder involved in food traceability. The table serves as a proposed framework that can be customized based on an organization's specific needs. The objective is to provide a comprehensive and structured view of the critical data needed for traceability. By recording this information on a blockchain ledger, stakeholders can verify the authenticity and quality of food products while consumers gain full transparency, enabling them to make informed purchasing decisions.

The information categories span farm operations, crop details, manufacturing processes, transportation conditions, and sales data. This ensures an end-to-end traceability system that enhances trust, security, and efficiency throughout the supply chain.

Table 3. Key Information for Blockchain-ACL-Based Food Traceability System

No.	Information Required	Stakeholder Role
	Farm Information	Farmer
1.	Farm Location (GPS Thank you for reaching out. address)	
2.	Farm certification	
3.	Farmer's contact information	
	Crop Information	
4.	Crop type	
5.	Planting date	
6.	Harvest date	
7.	Pesticide and fertilizer usage	
	Batch Information	
8.	Batch ID	
9.	Quantity Harvested	
10.	Packaging date	

	Environment Information	
11.	Temperature and humidity	
12.	Soil moisture and pH	
13.	Light intensity	
14.	Rainfall	
	Processing Information	
15.	Processing facility location	
16.	Processing date and time	
17.	Processing methods (e.g., pasteurization, sterilization)	
18.	Additives and preservatives used	
	Batch Information	Manufacturer
19.	Batch ID	
20.	Quantity processed	
21.	Packaging date	
22.	Expiration date	
	Transportation Information	
23.	Transportation mode (truck, ship, rail)	
24.	Transportation route	
25.	Departure and arrival dates and times	
26.	Temperature and humidity during transit	Distributor
	Batch Information	
27.	Batch ID	
28.	Quantity shipped	
29.	Recipient information	
	Storage Information	
30.	Storage facility location	
31.	Storage conditions (temperature, humidity)	
32.	Shelf life	
	Sales Information	Retailer
33.	Date of sale	
34.	Quantity sold	
35.	Customer information (if applicable)	
	Product Information	
36..	Product name	
37.	Brand	
38.	Barcode or QR code	
	Purchase Information	Consumer
39.	Purchase date	
40.	Purchase location	
	Traceability Information	
41.	Ability to trace the product back to its origin	
42.	Information on the product's journey from farm to table	

3.5. Phase D: Technology Architecture

With the data and application requirements established in the Information Systems Architecture phase, the Technology Architecture phase in TOGAF focuses on defining the infrastructure and platforms necessary to support the organization's business processes and applications. This includes hardware, software, networks, and other IT components that form the system's backbone. In the context of the proposed blockchain-based food traceability system, this phase emphasizes the implementation of ACLs to manage data access securely and efficiently.

Given the extensive data recorded by stakeholders—including farmers, manufacturers, distributors, and retailers—it is crucial to ensure that each stakeholder can only access relevant information. Role-based ACLs provide a structured mechanism for assigning permissions, ensuring that each entity interacts only with data pertinent to its role. Figure 6 illustrates a sample implementation of role-based ACLs, where permissions are granted based on data relevance. A special request mechanism can be introduced for stakeholders requiring access to restricted data to maintain security and privacy while allowing controlled access when necessary.

This approach enhances data privacy and security, fostering trust among stakeholders by preventing unauthorized access to sensitive information. The proposed system establishes a scalable, resilient, and secure technological foundation that supports an efficient and transparent food traceability system by leveraging ACLs within a blockchain framework.

3.6. Evaluation and Validation

Beyond the design and implementation of the framework, this study emphasizes the importance of evaluation to ensure its practical applicability. The proposed framework will be tested through pilot implementations and simulations within a controlled supply chain environment, allowing for a real-world assessment of its usability, data accuracy, and scalability. Stakeholder feedback will be collected to refine the system, address potential usability concerns, and ensure seamless integration with existing supply chain operations. Additionally, future studies will explore the framework's performance under varying operational conditions to assess its robustness and adaptability.

A critical component of the evaluation process involves comparing the proposed framework with existing blockchain-based food traceability solutions that incorporate access control mechanisms. While prior studies provide valuable insights, they also present certain limitations compared to our approach.

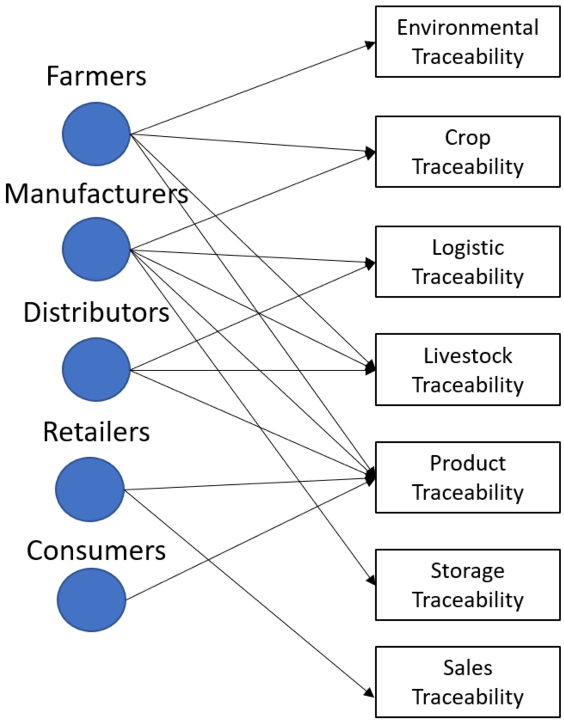

Figure 6. Example of How Role-Based ACLs Can Be Implemented

For instance, a study by Spitalleri et al. [45] introduced a platform that registers and visualizes the entire transformation and transportation process within the food supply chain. However, it does not explicitly integrate ACLs to manage data access permissions among stakeholders, a key differentiator of our proposed framework in ensuring data security and privacy. Similarly, Moudoud et al. [46] proposed a blockchain-based architecture for IoT-enabled supply chains, incorporating a lightweight consensus mechanism to enhance efficiency. However, it lacks a structured enterprise architecture framework, such as TOGAF, which our study leverages to ensure system scalability, adaptability, and alignment with business objectives.

While these studies do not explicitly incorporate TOGAF, they provide valuable insights into integrating blockchain and access control mechanisms within food traceability systems. This highlights a potential research gap, where the combination of TOGAF, blockchain, and ACLs could be further explored to enhance food traceability frameworks, particularly regarding security, scalability, and enterprise-wide adoption.

To evaluate the proposed food traceability framework, key considerations include data accuracy, which ensures precise and verifiable records throughout the supply chain, and usability, assessed through stakeholder feedback on the system's efficiency and user experience. Scalability is examined by analyzing the framework's ability to accommodate increasing data volumes and transactions over time. Additionally, data privacy and security are validated by assessing the effectiveness of ACLs in restricting unauthorized access while maintaining necessary transparency. Finally, operational feasibility is evaluated through pilot implementations, ensuring that the framework seamlessly integrates with existing supply chain processes and supports real-world applications.

3.6.1. Benchmarking as a Guideline for Future Studies

This study does not conduct benchmarking, as it focuses on developing a structured framework for blockchain-based food traceability. However, it proposes a set of evaluation criteria that can guide future benchmarking efforts, allowing researchers and industry practitioners to assess similar frameworks based on key performance factors. To facilitate such comparisons, future research can evaluate food traceability frameworks based on data accuracy, usability, scalability, security, and operational efficiency.

Data accuracy assesses the framework's ability to maintain reliable, tamper-proof records across the supply chain, ensuring transparency and trust. Usability measures how effectively stakeholders interact with the system, which is evaluated through user feedback and ease of adoption. Scalability refers to the system's capacity to handle increasing transaction volumes and expand across multiple supply chain networks without performance degradation. Security and privacy are assessed by examining the effectiveness of ACLs and blockchain security mechanisms in protecting sensitive data while maintaining controlled access for audits and compliance. Lastly, operational efficiency evaluates the framework's ability to optimize supply chain processes, reduce delays, and enhance decision-making.

By establishing these benchmarking criteria, future research can develop comparative analyses to assess various blockchain-based food traceability solutions, ensuring that emerging frameworks meet high transparency, security, and efficiency standards.

4. Conclusion

This framework paper presents a structured, scalable, and secure approach to addressing the challenges of food traceability by integrating TOGAF-driven enterprise methodologies, blockchain technology, and ACLs. The proposed framework enhances transparency, data integrity, and stakeholder trust while ensuring adaptability to evolving industry regulations. TOGAF's ADM provides a systematic roadmap for aligning business processes with technological innovations, facilitating efficient blockchain deployment while maintaining scalability and security. Blockchain's decentralization, immutability, and transparency mitigate data tampering and visibility issues, while ACLs strengthen data privacy through granular access controls, creating a harmonized balance between security and openness. The practical implications of this framework extend to enhancing operational efficiency, reducing food safety risks, and fostering consumer confidence by enabling end-to-end traceability across the food supply chain. Additionally, its scalability ensures applicability across diverse agricultural contexts, from small-scale farms to multinational supply chains, reinforcing compliance with global food safety standards. In conclusion, this framework paper provides an innovative and structured model that advances transparency, accountability, and efficiency in food supply chain management, offering valuable insights for policymakers, industry leaders, and technology developers to enhance food security and consumer trust on a global scale.

5. Declarations

5.1. Author Contributions

Conceptualization, T.O.K.Z. and K.S.M.A.; methodology, T.O.K.Z. and K.S.M.A.; validation, S.M., B.B., and Su.M.; formal analysis, Y.Y. and Su.M.; investigation, T.O.K.Z., S.M., and B.B.; resources, K.S.K.; writing—original draft preparation, T.O.K.Z. and S.M.; writing—review and editing, K.S.M.A.; visualization, K.S.K. and R.K.; project administration, Y.Y. and R.K. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

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5.4. Institutional Review Board Statement

Not applicable.

5.5. Informed Consent Statement

Not applicable.

5.6. Declaration of Competing Interest

The authors 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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