Blockchain technology for agriculture traceability systems in South Africa

Submitted to

Graduate School of Business
University of Cape Town

In partial fulfilment of the requirements for the degree of
Master of Management
(Specialising in International Management)

by

Ulrich Brummer

BRMULR001

May 2024

Supervisor: Prof Gary van Vuuren
Course Convenor: Dr Badri Zolfaghari

Plagiarism Declaration

1. I know that plagiarism is a serious form of academic dishonesty.
2. I have read the document about avoiding plagiarism, am familiar with its contents and have avoided all forms of plagiarism mentioned there.
3. Where I have used the words of others, I have indicated this using quotation marks.
4. I have referenced all quotations and properly acknowledged other ideas borrowed from others.
5. I have not and shall not allow others to plagiarise my work.
6. I declare that this is my own work.
7. I attach the summary of the Turnitin match overview (when required to do so).

Signature: Signed by candidate

Date: 4-Dec-23

Abstract

This research explores the integration of blockchain technology in South Africa's agricultural sector to enhance food traceability. The study critically examines the evolving landscape of agri-food markets, transitioning from traditional to modern supply chains marked by globalisation and increased emphasis on quality and safety. The role of blockchain technology in addressing traceability challenges is assessed through an extensive literature review, featuring diverse perspectives and insights.

The study investigates the application of blockchain in food traceability through an analysis of various models and frameworks presented in contemporary research studies. Notably, the research highlights the significance of traceability in ensuring food safety, quality, and sustainability, emphasising the growing consumer demand for transparent information about the origin and journey of food products. Past global food scandals have highlighted the need for robust traceability systems and highlighted the urgency of quick crisis identification and resolution.

Blockchain technology emerges as a transformative solution for food traceability, offering immutability, transparency, and decentralised control. The study acknowledges the challenges associated with blockchain adoption, including issues related to data governance, interoperability, regulatory frameworks, implementation costs, and the need for stakeholder education. The research underscores the importance of sector-wide consensus and standardisation efforts to overcome these challenges and facilitate the transition from blockchain pilots to enduring implementations.

The research is concluded by highlighting the implications of blockchain adoption, including enhanced transparency, improved food safety, and increased consumer confidence. It emphasises the need for collaborative efforts between government and industry stakeholders to establish supportive regulations and standardised protocols. The study identifies research gaps, including the exploration of advanced consensus mechanisms, privacy-preserving techniques, and the integration of artificial intelligence for data analytics. Continuous research and collaboration are proposed to address these gaps and drive ongoing innovation in the field.

The study provides a comprehensive overview of the current state of blockchain technology in South African agriculture, offering insights for practitioners, policymakers, and researchers to navigate the dynamic intersection of technology and food traceability.

Key Words: South Africa, Agriculture, Blockchain Traceability

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AI: Artificial Intelligence

BCT: Blockchain Technology

BIO: Biological

CPU: Central Processing Unit

CSR: Corporate Social Responsibility

Dapps: Decentralised Applications

DIP: Decentralised Insurance Protocol

DLT: Distributed Ledger Technology

DOCG: Denominazione di Origine Controllata e Garantita

ETH: Ethereum

GDP: Gross Domestic Product

GFSI: Global Food Safety Initiative

IBM: International Business Machines Corporation

ICT: Information and Communication Technology

IoT: Internet of Things

IPFS: InterPlanetary File System

JD.com: Jingdong, Chinese e-commerce

NFC: Near Field Communication

ORQs: Open Research Questions

PoW: Proof-of-Work

QR codes: Quick Response codes

RFID: Radio-Frequency Identification

SDGs: Sustainable Development Goals

SkuChain: Stock Keeping Unit Chain

USDA: US Department of Agriculture

WCBTP: Walmart China's Blockchain Traceability Platform

WSN: Wireless Sensor Networks

1. INTRODUCTION

1.1. Research Background & Problem Statement

The emergence of blockchain technology (BCT) as a key force has characterised the modern landscape of globalisation, which is characterised by the seamless flow of goods, services, information, and capital across international borders. This technological advancement has garnered substantial attention in academic and industrial spheres, particularly within the agriculture sector. The intersection of blockchain and agriculture is notable for its potential to address issues of traceability, security, and transparency, thereby transforming conventional practices.

One illustrative case highlighting the potential of blockchain technology is its adoption by major retailers, exemplified by Walmart's initiative in response to the 2018 foodborne disease outbreak in the US. The incident underscored the challenges faced by retailers in tracking the origins of their produce and set the stage for the adoption of blockchain technology, with its decentralised database architecture, as a contentious yet promising solution.

Since its introduction in 2016, blockchain technology has catalysed a seismic transformation in the agricultural industry. Its core attributes—security, transparency, and immutability—have revolutionised data management practices, ranging from crop production intricacies to intricate supply chain transactions. Central to this transformation is the concept of traceability, a cornerstone in ensuring food safety and cultivating customer trust. Notable implementations, such as Walmart China's Blockchain Traceability Platform (WCBTP), exemplify the tangible results achievable through blockchain-based traceability systems.

Beyond traceability, blockchain technology holds immense potential for the agricultural industry, offering streamlined solutions such as the automation of complex contractual exchanges through smart contracts and secure storage of land and property records. In the face of challenges like growing populations, climate change, and biodiversity destruction, innovation is needed, such as blockchain technology, to help make agriculture more profitable for both small- and large-scale farmers by guaranteeing food safety and enhancing traceability.

As we delve into the multifaceted tapestry of blockchain technology, this research endeavours to unravel its potential in tracing food produce from farm to consumer. The focus lies on elevating food safety standards and streamlining logistics management throughout the expansive food and agricultural production chain. However, despite manifest benefits, the adoption of food traceability in South Africa encounters persistent challenges warranting closer examination.

In the postmodern era of globalisation, where interpersonal interactions and the exchange of goods and information form the basis of all activities, blockchain technology stands out as a fundamental player. Acknowledging its significance in the agricultural sector, this paper aims to review the main applications of blockchain, with a particular focus on South Africa. The subsequent sections will delve into the definition and characteristics of blockchain technology and its applications in the agricultural sector.

The paper aims to contribute to the growing body of knowledge about blockchain technology and its potential to revolutionise the agricultural industry, especially in South Africa. By examining the various applications of blockchain, particularly in traceability, this study will provide valuable insights into how this technology can enhance transparency and accountability in the agricultural supply chain.

1.2. Research aims and objectives

Since 2016 there has since been a significant increase regarding the efficacy and practicality of applying blockchain technology to food traceability in the agriculture industry (Niknejad, Ismail, Bahari, Hendradi, & Salleh, 2021). The objective of this research study is thus to analyse the different characteristics of the South Africa agricultural industry, an investigation necessary to understand and how blockchain technology may be implemented to help the traceability of food or produce.

The following research questions have been established:

- What are the principal characteristics of food traceability in the South African agricultural sector.
- What are the projects which have already been undertaken?
- How may blockchain based food traceability be effectively implemented in the South African agricultural sector?

The research thus aims to achieve the following:

- Establish precedent in South African food traceability - (i.e., what projects have been undertaken?).

- Establish best practice from similar projects conducted globally.
- Determine whether similar practices would work in South Africa (i.e., what would hinder progress and what would benefit progress?).

To address these research aims and questions, a theoretical review of previous empirical research and practical considerations was adopted. This was done to investigate the potential of blockchain technology in enhancing food traceability within the agricultural industry in South Africa. This involved examining the current state of food supply chain, and identifying challenges and opportunity for improvement.

The research sought to contribute to a better understanding of the challenges and opportunities associated with the adoption of blockchain technology in agriculture in South Africa and help guide stakeholders seeking to improve food traceability and safety.

1.3. Research assumptions and ethics

Saunders et al. (2019) articulates that research ethics involve the application of ethical values, principles, and standards to guide a researcher's conduct. Expanding on this, the ethical framework encompasses the principles of autonomy, justice, and non-maleficence. It also directs the use of research methods that respect the rights, safety, and well-being of participants, ensuring the reliability, validity, and ethical soundness of the collected data. Consistent with Walliman's (2011) perspective, this ethical commitment extends to codes of conduct aimed at preventing harm to any party involved in the research process.

In the forthcoming exploration of blockchain technology's relevance to food traceability, based on previous research, a heightened emphasis will be placed on safeguarding the interests of authors associated with relevant research. In alignment with the refined ethical framework, the goal is not only to represent these authors accurately and fairly but also to prevent any potential harm to their prior work. This approach aligns with the ethical principles outlined by Saunders et al. (2019) and Walliman (2011)and serves as a proactive measure to uphold the integrity of previous research contributions.

Furthermore, the attainment of ethical clearance from the UCT Graduate School of Business is emphasised as a critical step to ensure compliance with ethical standards. This aligns with the commitment to ethical norms and guidelines, as demonstrated in the refined ethical framework.

2. LITERATURE REVIEW

2.1. Blockchain technology

2.1.1. Defining Blockchain technology

Satoshi Nakamoto, a pseudonym to conceal the identity of the entity responsible for the origination of Bitcoin (Nakamoto, 2008) was the birthplace of Blockchain technology. Nakamoto (2008) outlined a decentralised, peer-to-peer electronic payment system referred to as Bitcoin, which eliminated the need for third-party intermediaries and allowed for the secure and efficient transfer of digital funds. The system is powered by a shared distributed ledger, or blockchain, that records and verifies transactions, and allows users to track funds movements securely and anonymously without central authority intervention.

The development of Bitcoin and the underlying blockchain technology (a literal chain of blocks) revolutionised the financial landscape, making secure and transparent financial transactions accessible to all. The underlying blockchain technology is a type of decentralised, distributed "digital ledger technology" enabling secure, tamper-proof, anonymous, and immutable recordkeeping of digital data. Comprising a network of computers, or nodes, that store and updates records of digital data in a secure, distributed ledger stored across the network, all records are stored in a single shared ledger accessible to all in the network (Nakamoto, 2008). Raikwar et al. (2019) defined blockchain as a distributed ledger that stores a continuously increasing set of data which are validated by all participants.

Data stored in the blockchain are cryptographically secured and unalterable, meaning that they cannot be modified or deleted. Mavilia and Pisani (2022) argue that there is no unanimously accepted definition of Blockchain, but three conceptualisations of the technology may be defined.

- **Technically**, Blockchain is a distributed database comprising a ledger accessible to all users which may be publicly examined. It is not hosted on a single server but is instead stored on multiple computers, all synchronised in real-time.
- **Commercially**, it is a network in which users can perform transactions, exchange values, and exchange goods without the need for a central mediator.
- **Legally**, it can authenticate transactions, thus replacing the old, centralised bodies such as notaries, banks, and other financial intermediaries.

Demestichas et al. (2020) stated that every block in the Blockchain contains a minimum of the following fields:

- the block number (a numerical identifier assigned to each block in the blockchain, used to determine the order in which the blocks were created and for reference purposes)
- the stored data or transactions (data that are stored in a block within the blockchain. These data could include financial transactions, contracts, or any other type of data that are stored on the blockchain)
- the hash value of each previous block (a cryptographic code generated for each block and used to securely link each block to the previous one in the chain), and
- the hash value of the current block (a cryptographic code that is generated for the current block, used to link this block to the previous one in the chain securely (Nakamoto, 2008).

A nonce is another element in the block of the Blockchain. It is related to the concept of "mining" and is used in conjunction with the Secure Hash Algorithm 256 (SHA256) hashing algorithm to generate the hash of each block. SHA256 is part of the SHA 2 family of algorithms, and is a cryptographic hash function that generates a fixed-sized output value of 256 bits from input data, thus ensuring data integrity and security. It is most commonly used in blockchain technology and creates a unique fingerprint for blocks. This in turn provides a secure and tamper-proof ledger.

This hash is determined by four components, which include the block number, the previous hash, the stored data, and the nonce. As the block number, previous hash, and stored data

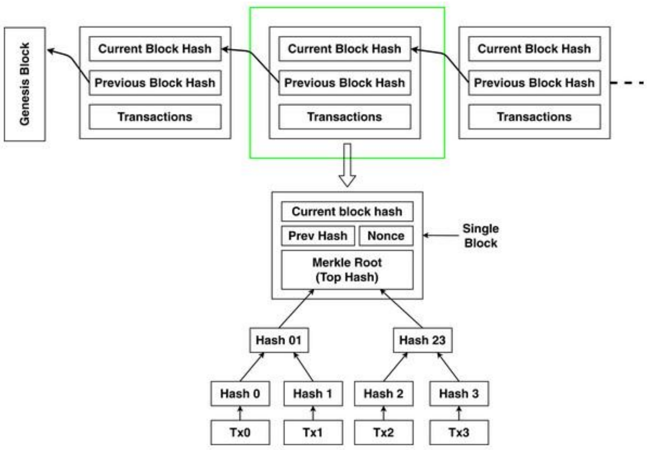

Figure 1: Structure of blockchain.

cannot be modified, as this would indicate that data tampering has occurred (Demestichas et al., 2020). Any attempt to modify the data contained in a block, alters the hash, severing the cryptographic link between it and succeeding blocks and thus making subsequent blocks invalid with no connection to the blockchain. Figure 1 (above) sets out the structure of blockchain as described above.

Proof-of-work (PoW) networks are a type of distributed consensus system that is used to validate transactions on a blockchain (Raikwar et al., 2019). This system involves miners having to solve cryptographic puzzles to create a new block and add new transactions to the blockchain (Demestichas et al., 2020). The mining difficulty indicator is used to determine the amount of work a node's computer must do to create a new block. As pointed out by Raikwar et al. (2019), in the Bitcoin blockchain the value is adjusted every 2016 blocks to consider the number of miners competing, the speed of their computers, and the amount of computing power available. This system of work allows for the network's security to be maintained, and malicious actors to be prevented from taking control of the network (Raikwar et al., 2019). However, a disadvantage of this system is centralisation (Demestichas et al., 2020) which occurs when more blocks are added than anticipated, leading to an increase in the difficulty level. When fewer blocks are added, mining difficulty reduces.

Decentralised applications (Dapps) serve as user interfaces, facilitating access and interaction with different elements of a blockchain. Instead of existing on a centralised server, these applications are decentralised programmes stored on the computers of peers within the blockchain network. The overarching objective of this technology is to establish a globally distributed supercomputer that leverages a blockchain for the immutable recording, tracking, and storage of all data, encompassing programmes and transactions. Notably, each client's device holds a copy of the blockchain application (Buterin, 2017). The creation of a decentralised network, driven by three primary reasons—fault tolerance, attack resistance, and collusion resistance—adds significant value. Decentralised systems exhibit heightened resilience against accidental failures, given their reliance on multiple components. Their resistance to attacks and manipulation is also enhanced due to the absence of vulnerable central points. The likelihood of collusion among participants is also mitigated, a notable contrast to corporate and governmental entities, which frequently prioritise self-interest to the detriment of others (Buterin 2017).

2.1.2. Prospective advantages of blockchain in Agriculture

As mentioned above, blockchain, the distributed ledger technology that underpins cryptocurrencies such as Bitcoin, provides a decentralised, secure, and transparent approach to data management and transaction recording. This rapid advancement in technology has opened new avenues for agricultural innovation, with blockchain technology emerging as a transformative force (Xiong et al., 2020). It offers enormous potential to revolutionise the agricultural sector with how data would be used for agricultural purposes.

The agricultural sector in South Africa plays an important role for the country's economy as it contributes to employment, food security and export earnings. In 2022, the agriculture sector represented 2.57% (R134 billion) of the Gross domestic profit (GDP) of South Africa (O'Neill, 2023). The sector employs roughly 870 000 people and the government states that it plays a fundamental role in the social and economic development of the country (Mavilia & Pisani, 2022). Despite the sector's level of importance, it continues to face challenges including food safety, supply chain inefficiencies, and fraudulent activities. The use of blockchain technology presents a viable solution to the challenges, as it possesses inherent capabilities that have the potential to enhance the overall effectiveness of the agricultural industry.

The inherent immutable characteristics of blockchain technology effectively act as a resilient deterrent against fraudulent activities by upholding an unalterable ledger of transactions and the origins of products. The implementation of this protective measure against the infiltration of counterfeit products into the market serves to enhance equity and openness throughout the agricultural supply chain, thereby ensuring the protection of the rights and welfare of both consumers and producers. This can be achieved through the implementation of effective traceability systems and the establishment of robust quality control measures.

The inherent traceability capabilities of blockchain technology enable the monitoring of agricultural product movements throughout the supply chain, starting from their origin and extending all the way to the consumer. This facilitates the rapid identification and isolation of contaminated batches in cases of foodborne illnesses. The implementation of transparency measures not only fosters consumer confidence but also promotes the uptake of sustainable farming methods.

2.1.3. Blockchain applications in agriculture

Expanding upon the potential benefits outlined in the preceding section, the integration of blockchain technology in the agricultural sector exhibits potential for innovative solutions and applications. The agricultural sector would be able to tackle a few challenges by utilising the decentralised, secure, and transparent attributes offered by blockchain technology. It is important to acknowledge that it is not a panacea for all agricultural challenges, particularly in South Africa. This section examines the various applications of blockchain technology in the agricultural sector. Agricultural insurance, smart agriculture, the agricultural supply chain are examined.

Agricultural Insurance

The integration of blockchain technology into agricultural insurance marks a paradigm shifts in risk management, responding to the escalating challenges posed by climate change and weather extremes (Lobell et al., 2011; Lesk et al., 2016 and Finger et al., 2018). Traditional indemnity-based insurances, while effective in providing precision coverage, grapple with adverse selection and moral hazard due to information asymmetry between farmers and insurers (Just et al., 1999). In response, Turvey (2001), suggested the development of index-based insurance as a compelling alternative. Payouts in these schemes are triggered not by the loss itself but by measurable indices, such as rainfall recorded at weather stations, reducing the impact of adverse selection and moral hazards (Barnett & Mahul, 2007).

The rise of smart index insurance contracts, exemplified by enterprises like Etherisc, WorldCover, and Arbol, accelerates momentum in the field (Jha et al., 2018). These initiatives employ blockchain to automate and expedite payouts, enhancing risk management efficiency in agriculture. Etherisc's decentralised crop insurance, denominated in DIP tokens, illustrates the feasibility of blockchain in addressing longstanding challenges (Mussenbrock, 2022).

However, the practicality of cryptocurrency payouts and the accessibility of blockchain-based insurance systems, especially for farmers in the developing world, present crucial challenges (Jha et al., 2018). Overcoming these challenges is vital for ensuring widespread adoption and equitable benefits of blockchain-enhanced agricultural insurance solutions. As the sector evolves, Gatteschi et al. (2018) propose the integration of external data sources through smart contracts and oracles, enhancing these blockchain applications by reducing basis risk and expediting the determination and payout processes. The ongoing evolution of blockchain-based solutions holds promise for revolutionising the agricultural insurance landscape, fostering resilience and sustainability in the face of dynamic environmental challenges.

Smart agriculture

Smart agriculture and precision farming are also expected to play a crucial role in this evolution. Smart Agriculture, at the intersection of the Internet of Things (IoT) and blockchain technology, revolutionises traditional farming practices. The core features encompass data and information management through the use of Information and Communication Technology (ICT) (Patil et al., 2018), IoT devices, and advanced data analysis tools. Blockchain, as a secure decentralised ledger, plays a pivotal role in ensuring transparency and immutability in agri-food systems. The technology addresses the vulnerabilities associated with centralised data management, preventing issues such as inaccurate data, distortion, and cyber-attacks (Pureswaran, 2016). Various models exemplify the synergy of IoT and blockchain, ranging from lightweight architectures for smart greenhouse farms (Patil et al., 2018) to comprehensive frameworks fostering trust among agricultural stakeholders (Lin et al., 2017). Companies like Fliament contribute by providing smart farming technology, enabling secure transactions against a blockchain. Moreover, blockchain facilitates transparency in farm organisations, as seen in Taiwanese farmland irrigation associations, where public access to blockchain-stored data enhances collaboration and resource management (Lin et al., 2017). It is, however, crucial to acknowledge the potential impact on the agricultural landscape, with larger farmers being better positioned to engage in blockchain-based smart agriculture, potentially exacerbating disparities between large and smallholders. This emphasises the need for inclusive approaches to ensure equitable benefits across the farming community.

Agricultural supply chain

The agricultural supply chain, a complex web of processes involving multiple stakeholders from producers to consumers, confronts pervasive inefficiencies that amplify the final cost of goods. Notably, operational supply chain costs constitute a significant portion, representing two-thirds of the ultimate product cost (Niforos, 2017). In response to these challenges, blockchain technology emerges as a promising tool, leveraging its technical and governance characteristics to instil transparency and traceability.

Blockchain's application in supply chain management, initiated since 2016, has garnered momentum, with a primary focus on traceability (Rijanto, 2020; Yadav & Singh, 2019). The technology's inherent capacity to store immutable records that are transparent and accessible to all users provides a robust foundation for tracing the journey of agricultural products from farm to fork. This traceability not only addresses concerns related to food safety but also enhances accountability and reliability in the supply chain.

Blockchain also facilitates the creation of digital identities, generating vast datasets from transactions within agricultural supply chains. Detailed records empower actors in the supply chain with accurate information, fostering better decision-making. Beyond its immediate applications, blockchain stands poised to integrate with emerging digital technologies like artificial intelligence, IoT, big data, and 3D printing, promising a comprehensive and continuously improving approach to managing the agricultural supply chain (Dujak & Sajter, 2019; Tripoli & Schmidhuber, 2018).

The success stories of AgriDigital and Louis Dreyfus Co. underscore blockchain's tangible impact in practice, from settling grain sales to expediting document processing and reducing manual checks in agricultural commodity trades. As blockchain continues to evolve and intertwine with cutting-edge technologies, it plays an increasingly important role in shaping the agricultural supply chain, offering enhanced levels of traceability, efficiency, and reliability (Kamilaris et al., 2019).

2.2. Smart Contracts

2.2.1. Defining Smart Contracts

The definition of smart contracts within academic and legal discourse remains notably varied, indicating the complexity and multifaceted nature of this innovative concept. There is not a single, widely accepted definition, as Szabo (1996) acknowledged almost three decades ago (Szabo, 1996). While early definitions, such as Szabo's (1996) description of smart contracts as "a computerised protocol that executes the terms of a contract," persist, contemporary interpretations reflect the evolution of technology and its applications (Szabo, 1996). Recent perspectives emphasise the self-executing and programmable aspects of smart contracts, underscoring their capacity to execute, enforce, and monitor agreements autonomously (Prause & Boevsky, 2019).

Szabo's (1996) original definition highlights the primary objectives of smart contract design, which aim to satisfy common contractual conditions, minimise exceptions, and reduce the reliance on trusted intermediaries (Szabo, 1996). These foundational principles have endured, forming the basis for subsequent definitions that capture the essence of smart contracts as executable code facilitating contract performance (Prause & Boevsky, 2019). Notably, a smart contract is considered a set of promises implemented in software, transcending its paper-based predecessors in terms of efficiency and automation (Szabo, 1996). This view aligns with the assertion that smart contracts function as autonomous entities executing predefined logic on a blockchain network (Prause & Boevsky, 2019).

Recent legal frameworks, exemplified by bills approved in Arizona and Malta, underscore the decentralised nature of smart contracts. They define smart contracts as event-driven programmes running on distributed, decentralised ledgers capable of taking custody and instructing asset transfers (Arizona House Bill 2417, 2017; The Malta Digital Innovation Authority Act, 2018). This decentralised attribute aligns with the broader category known as decentralised smart contracts, emphasising their execution on blockchain or similar distributed ledger technologies (Arizona House Bill 2417, 2017). The Cambridge Handbook of Smart Contracts further clarifies decentralised smart contracts as digital agreements written in computer code, executed on decentralised networks without requiring human intervention (de Caria, 2019).

The term "smart contract", however, lacks a universally accepted definition, leading to nuances in its interpretation. While consensus on core attributes exists, such as automatic execution through computer code, there is ongoing debate about the necessity of blockchain or distributed ledger technologies for a contract to be deemed "smart" (de Caria, 2019). This diversity in definitions mirrors the dynamic nature of technology and its ongoing impact on legal and contractual frameworks.

One aspect of contention revolves around the potential inclusion of artificial intelligence (AI) in smart contracts. Despite the contemporary understanding of "smart" suggesting AI involvement, historical definitions, including Szabo's (1996), explicitly exclude AI from smart contracts (Szabo, 1996). Scholars argue that the inherent logic of smart contracts, based on *"If this...then that,"* does not inherently require AI, emphasising that smart contracts enforce predefined lines of code without cognitive capabilities (de Caria, 2019).

The definition of smart contracts continues to evolve, reflecting advancements in technology and legal frameworks. The multifaceted nature of smart contracts encompasses their foundational principles articulated by Szabo, the contemporary emphasis on autonomy and programmability, and ongoing debates about decentralisation and AI integration. Understanding these diverse perspectives is crucial for navigating the complex landscape of smart contracts and their implications in various domains.

2.2.2. Smart contracts in agriculture

The integration of smart contracts in the agricultural sector signifies a notable shift, leveraging blockchain technology to improve traceability, streamline processes, and fortify the quality assurance of agricultural products. The inception of the idea of smart contracts dates to the 1980s, with Szabo pioneering the concept as a mechanism to embed contractual clauses within the hardware and software, making breaches prohibitively expensive (Szabo, 1996). The advent of Ethereum in 2016 brought this concept to life, providing a decentralised blockchain platform equipped with tools for implementing smart contracts (Tikhomirov, 2018). The combination of blockchain and smart contracts has opened avenues for innovative applications in agriculture and beyond. Given that Ethereum operates as a blockchain, the act of storing the contract within the blockchain presents a significant obstacle to unauthorised access and manipulation of said contract. Figure 2 shows the standard process for constructing and executing smart contracts.

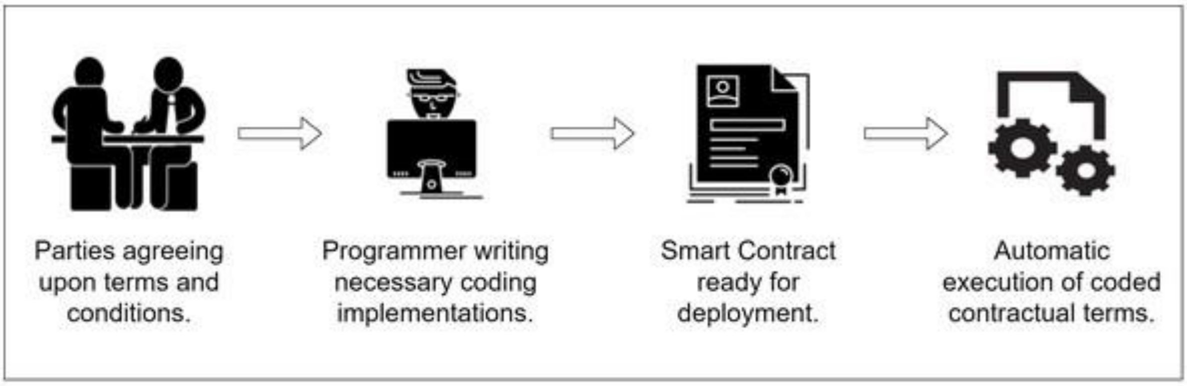

Figure 2: The steps in building a smart contract.

In the agricultural domain, smart contracts find application in diverse areas, ranging from supply chain management to intellectual rights management. Chang, Chen, and Lu (2019) exemplify the utilisation of smart contracts at the core of a system design, automating processes in a supply chain, ensuring real-time tracing of products, and maintaining control over every step involved. Similarly, Hasan et al. (2020) integrate smart contracts in an industrial spare parts traceability system, utilising smart contracts to implement necessary functions, modifiers, and events, ensuring a streamlined and automated process.

Trust establishment between parties in agricultural processes is a critical aspect addressed by smart contracts. Bader et al. (2018) propose a smart contract-based car insurance ecosystem named CAIPY, where smart contracts guide the step-by-step execution of the insurance policy and interact with tamper-proof IoT devices for real-time information about the car's condition. The implementation of smart contracts enhances security, making it challenging to breach or tamper with the contract (Bader et al., 2018). Smart contracts also extend their applicability to intellectual property rights management. Zhao and O'Mahony (2018) showcase BMCProtector, a music copyright management system employing blockchain and smart contracts to automate processes from music creation to royalty distribution, ensuring transparency and security in the music industry.

Attributes, functions, modifiers, and events emerge as common terms encountered in coding smart contracts (de Caria, 2019). Attributes, representing variables that hold values, can range from primitive data types to more complex structures. Functions denote mechanisms or tasks within the system, executed upon invocation. Modifiers define access powers for various actors or components within the contract, while events facilitate the logging of transaction data in the blockchain's transaction logs for auditability (de Caria, 2019).

Expanding into the agricultural supply chain, the integration of smart contracts, blockchain, and IoT devices proves instrumental in achieving traceability and process development. Pavithra and Balakrishnan (2015) highlight the effectiveness of IoT devices for real-time monitoring and data collection in various applications. By incorporating blockchain as a secured backbone, concerns related to information security in IoT-based devices are effectively addressed (Mohanty et al., 2020).

The combination of blockchain, IoT, and smart contracts lays the foundation for a secure, transparent, and automated system for traceability and process management in agriculture (de Caria, 2019). Research studies, such as those by Kim et al. (2018), Lin et al. (2020), and Lucena et al. (2018), showcase how this integration can revolutionise food traceability, agricultural ecosystem management, and quality assurance in grain exports.

The incorporation of smart contracts in agriculture presents a revolutionary shift in enhancing trust, transparency, and efficiency across various facets of the agricultural supply chain. From supply chain management to intellectual property rights, smart contracts prove to be a versatile and indispensable tool, laying the groundwork for a technologically advanced and secure agricultural landscape.

2.3. Traceability

2.3.1. Defining Traceability

Traceability is a principle commonly referred to as the ‘one-step-back-one-step-forward’ approach, which involves the ability to identify the source of food and feed ingredients and food sources. By implementing a traceability system, organisations can document and trace a product through the various stages and operations of manufacture, processing, distribution, and handling, from primary production to consumption. Through this system, the cause of the nonconformity of a product can be identified and corrective action, such as product recall or withdrawal, can be taken to prevent unsafe products from reaching consumers (Banerjee et al., n.d.). Golan et al. (2004) defined traceability as a system that tracks the movement of food products through the food supply chain, allowing the food industry to identify the source of a foodborne illness or recall quickly.

Traceability systems help ensure food safety by providing information about the origin and movement of food products, and the ability to trace back any contamination or safety issues. Traceability also reduces food production waste and increases food production efficiency while protecting consumers from foodborne illness. Aung et al. (2014) asserted that traceability is the ability to track the production history, environmental and social impacts, and compliance data of food products from the grower to the consumer. It is enabled by information technology systems that store and analyse vast volumes of data and provide a standard means of communication available to all members of the food supply chain. A more comprehensive, informed, and revised definition of food traceability was provided by Bosona and Gebresenbet (2013), who defined traceability as tracking food throughout the supply chain, involving the capturing, storage and communication about food, feed, and food-producing animals/substances at all stages. This allows products to be monitored for safety, quality control, and traceability, both up and down the chain.

2.3.2. Food Traceability in principle

Food traceability is a system used to track the movement of food items and ingredients throughout the food supply chain, allowing food producers, distributors, and retailers to identify the source and history of a food product, from origin to final point of sale. Traceability is an important component of food safety and food security, as it helps to ensure the safety and quality of food by allowing companies and regulators to quickly identify and address any potential food safety issues, from contamination to spoilage. Aung et al. (2014) identified three main characteristics of traceability systems. Traceability systems typically involve the use of a unique identifier, such as a barcode, RFID tag, or serial number, to track the movement of products and ingredients through the supply chain. This tracking information is then stored in a centralised database, allowing companies to quickly access data on the origin and history of a product. Traceability systems can be used to provide traceback information in case of a food safety issue, such as a recall or contamination event. The implementation of food traceability systems is supported by several international standards and regulations, such as the Global Food Safety Initiative (GFSI) (2022). These standards provide guidance on how companies should establish and maintain traceability systems, with the goal of ensuring the safety and quality of food products.

Traceability in the food supply chain can be broken down into three distinct types depending on the activity or direction in which information is recalled, namely:

- back traceability, also known as supplier's traceability, which entails tracking a product's movement from the supplier to the point of sale.
- internal traceability, or process traceability, which involves monitoring the product's journey from production to point of sale and
- forward traceability, or client traceability, which involves recording a product's journey from the point of sale to consumer (Perez-Aloe et al. (2007))

Each type of traceability provides insight into the product's journey, allowing for effective product recall and communication between stakeholders in the food chain. Backward traceability or tracing is the capability of an information system to identify the source and characteristics of a product, based on one or several given criteria, at any point of the supply chain. Backward traceability thus enables tracking the point of history and origin.

In contrast, forward traceability or tracking is the capability of an information system to locate a product, based on one or several given criteria, at any point of the supply chain. This enables monitoring of a product's journey, from current location to destination. It is essential for an information system to have the capability to support both types of traceability to ensure the effectiveness of the system, as success with one type of traceability does not necessarily imply success with the other (Kelepouris et al., 2007).

3. RESEARCH METHODOLOGY

3.1. Strategy and Approach

Three possible approaches to theory development are possible (Saunders et al., 2019). These theory developments are *inductive, deductive*, and *abductive*. The methodology of deduction involves the development of an idea or theory or logical conclusion which is derived from literature. This theory is then subjected to tests to determine the anticipated phenomena. For this study, which focuses on blockchain for food traceability in the South African agricultural market, the *deductive* approach was selected.

The purpose of the study is to perform an analysis of the field of blockchain technology in food traceability within the South African agricultural industry, while also examining global research in this field. Exploring both local and international perspectives would help to provide a holistic understanding of the applications and implications of blockchain technology in enhancing food traceability within the agricultural sector. The scientific field accumulates knowledge over time, with each topic or research project being based on previous research and knowledge that had been done by other researchers. The bibliographical review is a methodological approach of observational research. A bibliographic review uses a retrospective approach as an observational research methodology (Ocaña-Fernández & Fuster-Guillén, 2021). It is systematic in its approach to thorough selection, complete analysis, comprehensive interpretation, and extended discussion of theoretical frameworks, research findings, and conclusive insights offered in contemporary scientific articles on a certain chosen topic. The primary goal of performing a bibliographic review is to extract and synthesise useful or important information from this body of existing literature, therefore significantly contributing to the resolution of relevant research problems. This technique provides a disciplined and intelligent manner of navigating the academic terrain for university students and professionals involved in research activity.

The output is a strict and systematic review layout which encompasses a wide range of relevant facts. Through compiling a vast body of scientific information accumulated within the chosen topic, one can provide a nuanced conclusion that serves as a concise summary of the thoughts and discoveries acquired through substantial scholarly research. Through meticulously examination of the available literature, ongoing research paths can be discovered and any obvious gaps in the known understanding of the subject area (Esquirol-Caussa & Sanchez-Aldeguer, 2017).

A bibliographical review must be conducted to gain a thorough understanding of blockchain technology in food traceability within the agricultural industry of South Africa and the research issues faced in this field. A comprehensive bibliographical review must clearly and correctly define the topic as well as the research question. An extensive search and collection process of all the relevant information is then required, followed by an analysis and selection of all the gathered information. A systematic writing review of all the research and appropriate information is then performed, followed by a conclusion that summarises all the research done, and knowledge gained in the area (in this case, the field of blockchain technology in food traceability within the agricultural industry of South Africa). This method also helps with identifying research areas that have not been thoroughly reviewed previously.

The research strategy is a plan of how researchers will achieve their goal of answering their research question or questions. The type of research question asked directs the research aims and helps guide the researcher to a relevant and appropriate research strategy. Qualitative studies are likely to cause confusion when deciding on a strategy because of the diversity of qualitative strategies (Saunders et al, 2019). Eight strategies are available for qualitative design selection:

- experiments,
- surveys,
- archival and documentary research
- case study
- ethnography
- action research
- grounded theory, and
- narrative inquiry.

For this research study, an *archival/documentary* and *case study research* approach were selected. Archival and documentary research strategies are appropriate in cases where secondary research (rather than the collection of primary research) is used to review the data (Saunders et al., 2019). Case studies must be carefully chosen, and study boundaries clearly established to effectively assess the topic dynamics.

3.2. Research design, data collection & strategy

3.2.1. Research design

A comprehensive literature survey on the intersection of food traceability and blockchain technology requires a well-thought-out research design. The objective is to identify, analyse, and synthesise existing knowledge in this rapidly evolving field.

The research questions that the literature survey aims to address is clearly articulated, covering the impact of blockchain on food traceability, challenges faced in implementation, regional variations, and emerging trends. The objectives to guide the scope of the literature review are clearly set out.

Specific criteria for including or excluding sources are developed (e.g., a focus on peer-reviewed articles, recent publications, and studies relevant to the technological, regulatory, and practical aspects of implementing blockchain in food traceability). Exclusion criteria involve outdated sources or publications in languages not understood by the researcher. A comprehensive list of keywords related to food traceability and blockchain has been developed including terms like "blockchain technology," "food supply chain," "traceability," and "smart contracts." Relevant databases such as PubMed, IEEE Xplore, Scopus, and academic journals in information systems, agriculture, and supply chain management have been identified.

Systematic searches using the identified keywords in the selected databases were instituted and the established inclusion and exclusion criteria to the search results applied. Titles and abstracts were screened to identify relevant articles. The full texts of selected articles were assessed to ensure they align with the research questions and objectives. Transparency in the selection process was maintained to enhance the review's reproducibility.

A thematic coding framework to categorise and organise the selected literature was implemented including technological advancements, regulatory considerations, challenges faced, case studies, and future directions. This framework guided the systematic analysis and synthesis of information across different studies.

Pertinent information from each selected source, including key findings, methodologies employed, and notable gaps or limitations, was gathered. This information was systematically synthesised to construct a coherent narrative that addresses the research questions and objectives. Patterns, trends, and contradictions across the literature were identified and discussed.

The quality and rigor of the selected literature was interrogated, taking accounting of factors such as the research design, sample size, and methodology. Distinction was made between empirical studies, theoretical frameworks, and practical case studies, to ensure that the synthesised information was robust and reliable.

The diverse nature of the food industry across regions and sectors was recognised and the literature survey tailored to account for regional variations in food supply chains, regulatory frameworks, and technological infrastructures. This nuanced approach ensured a comprehensive understanding of the global landscape while acknowledging local intricacies.

3.2.2. Data collection

The research strategy used for the presented study is archival, documentary research and case studies. According to Saunders et al. (2019) secondary data refers to data that have already been collected for the purpose of another study. Pre-assembled data may be analysed and interpreted to provide additional information. As the field of blockchain and traceability is growing rapidly, more research is being done in the field. The secondary data, for the purpose of this research, would be collected through conducting searches on the GSB library website as well Google scholar articles. To ensure that the field of blockchain technology and food traceability in South Africa is thoroughly covered, many relevant articles will be explored. Work that builds on the literature from outside South Africa is also interrogated.

3.2.3. Data Analysis

To conduct a comprehensive literature review and analysis of case studies, data and relevant information will be extracted from various articles. To do this, a literature review table will be used to provide an overview of blockchain technology in food traceability in South Africa. The most significant research studies presenting different blockchain models would be identified to create a clear understanding of the topic:

- the author/authors,
- the year of publication of the previous study,

- the title of the previous study done.

3.3. Research Criteria

Replication of a research study is essential to ensure its validity and establish its reliability. Through replication, another researcher can confirm the previous results and detect any potential errors or biases that may have been present in the original research. By replicating the study, researchers can also suggest improvements or further investigations that could be made to the original research (du Plooy-Cilliers et al., 2014).

Qualitative validity is the accuracy and credibility of a research paper's findings. It is determined by the strength of the research methodology and data analysis, as well as the researcher's ability to draw meaningful conclusions from their findings. Qualitative validity is important because it helps to ensure that research results are reliable, valid, and transferable.

To assess the qualitative validity of a research paper, it is important to consider the research design, sampling methods, and data collection techniques used. The research design should be appropriate for the research questions being addressed and provide a clear path from the research question to the conclusion. The sampling method should be representative of the population being studied, and the data collection techniques should be appropriate for the research objectives.

It is also important to consider the researcher's ability to interpret the findings. Meaningful conclusions must be gleaned from (and conclusions supported by) the appropriate data. Implications of the findings and recommendations for further research are also imperative as is effective communication of research results. The thesis should be logically structured, organised, and presented in a way that is easy to understand. In addition, clear and concise explanations of the research process and results should be provided.

3.4. Limitations

As the research will make use of secondary data, the validity of previous research conducted must be relied upon. Blockchain technology is a relatively new field and the application to food traceability is a niche market, which could lead to less research having been conducted in the field. The case of having to communicate with suppliers in the agricultural industry in South Africa must be considered as requisite information might not be easily and openly attainable.

4. RESEARCH FINDINGS

4.1. Pincheira Caro, Salek Ali, Vecchio & Giaffreda (2018)

4.1.1. Summary

The paper introduces AgriBlockIoT, a decentralised, blockchain-based traceability solution designed for Agriculture and Food (Agri-Food) supply chains. Current traceability systems in Agri-Food often rely on centralised infrastructures, leading to concerns about data integrity, tampering, and single points of failure. AgriBlockIoT leverages blockchain technology, known for its fault-tolerance, immutability, transparency, and traceability features, to address these issues. The system aims to seamlessly integrate IoT devices along the Agri-Food supply chain, allowing for the reliable and auditable tracking of products from farm to fork. A use-case scenario is described which implements two different blockchain platforms: Ethereum and Hyperledger Sawtooth. The evaluation of both deployments includes a comparison of performance metrics such as latency, CPU usage, and network usage, highlighting their respective advantages and drawbacks.

4.1.2. Background

The paper addresses the limitations of traditional logistics information systems in Agri-Food supply chains, emphasising the need for transparency, traceability, and auditability to enhance food quality and safety, responding to consumer demands. It highlights the adoption of IoT technologies, such as Wireless Sensor Networks, but notes that current solutions often rely on centralised cloud infrastructures, presenting security concerns.

To address these issues, AgriBlockIoT, a fully decentralised traceability system for Agri-Food supply chain management, is introduced. The proposed solution leverages Blockchain technology, providing a peer-to-peer digital ledger that is tamper-proof, auditable, and transparent. By integrating various IoT sensor devices directly into the blockchain, AgriBlockIoT ensures traceable data at every step of the supply chain, eliminating the need for centralised intermediaries.

A use-case scenario, "from-farm-to-fork," representing a typical food traceability scenario from agricultural production to consumption is discussed, and two blockchain implementations, Ethereum and Hyperledger Sawtooth, are compared in terms of performance metrics, including latency, CPU load, and network usage.

4.1.3. Practical applications

The practical applications of the research involve assessing the performance of AgriBlockIoT, a decentralised traceability system for Agri-Food supply chain management. The functionality of an IoT sensing device that produces digital values directly stored in the blockchain is explored in which stored data can be retrieved, and smart contracts can be autonomously executed based on certain conditions in the data.

The research compares the performance of AgriBlockIoT on two different private blockchain implementations, namely Ethereum and Hyperledger Sawtooth, an assessment which includes latency, CPU load, and network usage metrics. The results indicate that Hyperledger Sawtooth outperforms Ethereum in terms of performance. Further practical applications include informing the choice of blockchain implementation for AgriBlockIoT to optimise its functionality and efficiency in real-world scenarios.

4.1.4. Conclusions

AgriBlockIoT integrates IoT and Blockchain technologies to create transparent, fault-tolerant, immutable, and auditable records for Agri-Food traceability systems. Practical tests show that the Hyperledger Sawtooth-based implementation had better metrics than Ethereum, but both have distinct properties. Factors such as scalability, reliability, software maturity, economic considerations, and consensus algorithm efficiency should be weighed when choosing between them. Ethereum may offer scalability but at a higher cost, while Hyperledger Sawtooth is more suitable for computationally limited devices. Future work includes extending the performance analysis to assess the framework's suitability for real IoT devices and gateways in Agri-Food supply chains, especially on more constrained hardware architectures.

4.2. Feng, Wang, Duan & Zhang (2020)

4.2.1. Summary

This paper explores the role of traceability in food quality and safety management, highlighting the limitations of traditional IoT traceability systems that often rely on a centralised server-client paradigm. The authors argue that blockchain technology, respected for its security and transparency, has the potential to enhance traceability in food supply chains. The paper aims to fill gaps in the existing literature by reviewing blockchain technology characteristics, proposing solutions for food traceability, and outlining the benefits and challenges of implementing blockchain-based systems. The study provides a framework and flowchart for the development and application of blockchain-based food traceability systems, offering valuable insights for researchers and practitioners to improve food traceability and contribute to food sustainability.

4.2.2. Background

The food industry's sustainability and consumer trust can be enhanced by ensuring transparency and authentication throughout the entire food supply chain. Traditional IoT traceability systems, using technologies such as RFID, WSN, and NFC, monitor and store information at various stages of production, distribution, and consumption. The centralised server-client paradigm of these systems presents challenges, however, as consumers struggle to access comprehensive transaction information and trace product origins. To build trust among participants in the traceability chain, there is a need for effective information management in agri-food as set out in Figure 3.

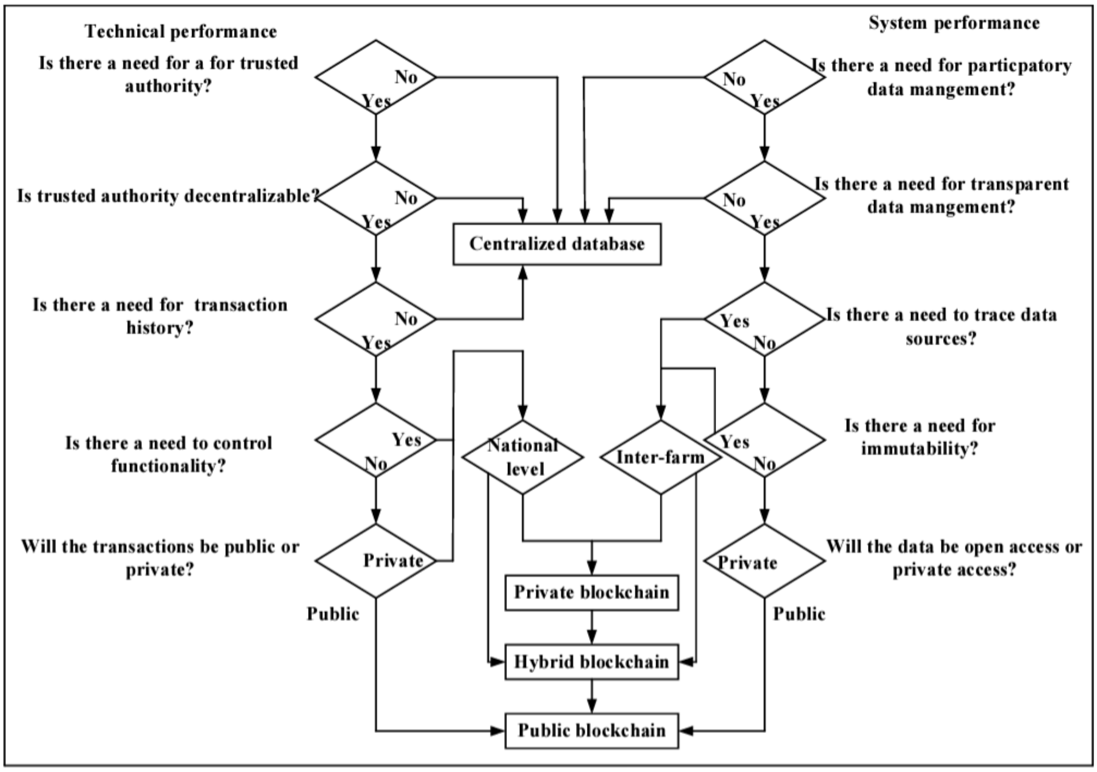

Figure 3: A flowchart of suitability and sustainability application analysis for blockchain-based traceability system.

The paper argues that improving traceability, transparency, security, durability, and integrity is crucial for addressing food safety and quality concerns. Blockchain technology arises as a promising solution, offering decentralised and tamper-proof features. Despite its potential, research gaps exist in understanding how blockchain can enhance food traceability, especially in terms of information transparency and security. The paper aims to fill these gaps by addressing key questions related to the implementation of blockchain-based IoT traceability systems, their benefits and challenges, and their impact on traceability trust mechanisms.

The authors propose reviewing blockchain technology characteristics, identifying blockchain-based solutions for traceability trust mechanisms, and highlighting the benefits and challenges of implementing blockchain-based traceability systems. The goal is to provide researchers and practitioners with valuable insights, including an architecture design framework and application feasibility analysis flowchart, to facilitate the understanding and application of blockchain technology in food traceability. The results of the study aim to contribute to improving traceability transparency and efficiency, thereby enhancing the security of the food chain and promoting food sustainability.

4.2.3. Practical applications

Stage 1: Farming – in the farming stage, IoT smart devices collect and transmit traceability data, including information on the environment, farming practices, and applications of substances. These data are stored in a blockchain-based traceability system, facilitating transactions between farmers and processors.

Stage 2: Harvesting – after harvesting, agri-food products' traceability information, such as date, time, and weight, is recorded in the blockchain-based traceability system before being transported to processing plants.

Stage 3: Processing – processing stages impact the quality and safety of products. Operators record traceability information, including processing conditions, batch transformations, and package details, in the blockchain-based system.

Stage 4: Logistics & Cold Storage – involve monitoring with IoT sensor devices to obtain traceability information on ambient conditions, storage locations, and transportation details. This information is stored in the blockchain to aid decision-making and reduce losses.

Stage 5: Consuming – information about sold products, including name, sale time, shelf life, and price, is stored in the blockchain. Consumers can access this information before making a purchase.

Examples of practical applications

Example 1 – Blockchain-based Traceability of Plant Food Production Chain

Smart contracts and IoT devices record the entire production process of plant food in the blockchain. Information, such as seeding quality, production conditions, and sales details, is transparently available throughout the process, enhancing traceability, sustainability management, and consumer trust.

Example 2 - Blockchain-based Traceability of Poultry

In a collaboration between Ali Cloud and ZhongAn Technology Company, blockchain technology is applied to achieve transparency in the chicken poultry supply chain. Each chicken wears a unique card, and data on location, movement, breed, environmental conditions, health, and slaughtering details are automatically collected and uploaded to the blockchain. Consumers can scan a QR code on the chicken card to trace the entire life cycle of the chicken, promoting transparency and trust in the supply chain.

Blockchain-based traceability systems enhance reliability and security through consensus mechanisms, ensuring transaction data integrity and preventing tampering. Integration with IoT devices further improves transaction efficiency. Information stored in multiple ledgers with encryption manipulation becomes resistant to attacks. Consensus mechanisms guarantee information integrity, safeguarding data against tampering by unanimous agreement in the traceability process. Blockchain facilitates interoperability and integration across organisational processes, fostering trust and collaboration among supply chain partners. The transparent, no-tampering history information enhances quality prediction and evaluation capabilities. Blockchain-based traceability systems provide reliable data at each traceability chain stage, contributing to more accurate shelf-life predictions and reducing economic loss and food waste. Blockchain enables end-to-end traceability operations, meeting the requirements to trace product origins comprehensively. Traceability information, from farming origins to shelf-life, can be entered into the blockchain at each production step, building trust among stakeholders and ensuring effective sustainability and transparency.

Scalability, security, and stability challenges in blockchain technologies for IoT traceability applications in the global food chain. Design limitations, consensus algorithm choices, transaction capacity, and data accessibility need further development for IoT platforms and services. Security infrastructure challenges in blockchain, including a lack of public-key infrastructure meeting quality traceability system requirements, such as inter-domain policies and control. The need for interoperability and standardisation between ledger types (public and private) to develop blockchain architecture standards for collaborative trust and information protection. Legal and regulatory issues related to data privacy influence the social and institutional challenges. A lack of clear legal regulations and standards for blockchain technology implementation in agri-food traceability requires the introduction of a legal framework. Ensuring continuous stability and security of blockchain-based IoT applications is a vital challenge for sustainable traceability management. Standardised test platforms should be evaluated for low-consumption, high latency, and storage capacity.

4.2.4. Conclusion

While blockchain technology holds promise as a solution to food traceability issues, a limited understanding of its specific characteristics, functionalities for traceability management, development and evaluation methods, and the associated benefits and challenges faced by researchers and practitioners continues. The research contributes to the field by providing a timely review of blockchain technology applications in sustainable traceability management. It offers theoretical and practical insights, advances understanding, and suggests avenues for further research and development in blockchain applications for sustainable food traceability systems. As review-based research, the proposed frameworks and guidelines are conceptual and require empirical validation. Future studies are encouraged to test and evaluate these frameworks in pilot applications, considering multiple perspectives, and addressing aspects such as hardware deployment, storage capability, transaction speed, and overall system performance. There is also a call for future research to explore how blockchain technology can enhance the sustainability of various agri-food chains.

4.3. **Mirabelli & Solina** (2020)

4.3.1. Summary

The study explores the application of blockchain technology in the agricultural sector, focusing on addressing food traceability issues. While blockchain has gained prominence in various fields such as finance, healthcare, smart cities, smart contracts, energy markets, and government, its potential in agriculture (particularly in ensuring the traceability of food products) is of increasing importance. The success of blockchain technology is attributed to its properties of reliability, transparency, and immutability.

The research aims to catalogue various methodologies proposed by scholars in the literature, identifying current research trends and potential future challenges in implementing blockchain for agricultural traceability. The necessity for an effective traceability system in agriculture arises from concerns such as the widespread use of harmful pesticides and fertilisers, emphasising the need to ensure food safety for consumers. Despite the increasing attention to blockchain in agriculture, the study finds that the technology is still in its early stages, with limited practical applications.

The study highlights that while there are numerous proposals in the literature, only a few applications have been implemented in real-world contexts. Scientific research in blockchain technology reveals that certain countries, including China, the US, and Italy, are actively investing in its development. While blockchain holds significant promise for enhancing traceability in the agricultural sector, there is still a considerable journey ahead to reach a mature stage of widespread adoption and application.

4.3.2. Background

The paper discusses the significant role of blockchain technology as a highly debated research topic, originally introduced by Nakamoto in 2008 for Bitcoin. While its initial application was in the financial sector, blockchain has expanded into various domains, including healthcare, smart cities, smart contracts, energy markets, and government. Its success is attributed to properties such as reliability, transparency, and immutability.

The paper focuses on the application of blockchain in agricultural supply chains, specifically for ensuring food traceability. Agricultural supply chains involve actors in farming, distribution, processing, and marketing, covering the journey "from field to table." Food traceability is crucial due to regulatory provisions and the need to address issues such as the widespread use of harmful substances like pesticides, fertilisers, hormones, and other chemicals in agriculture, posing risks to human health and reducing nutritional value.

The main purpose of the paper is to conduct a comprehensive literature review on the application of blockchain in agricultural supply chains, emphasising food traceability. This review aims to explore the relatively unexplored link between blockchain and food traceability in the agricultural context. While acknowledging a more general review on blockchain and agriculture, the paper distinguishes itself by its specific focus on food traceability. Given the rapid growth of blockchain and the increasing number of contributions, the study highlights the necessity to collect, catalogue, and classify different proposed methodologies to understand research trends and anticipate future developments or challenges.

4.3.3. Practical applications

The paper addresses the early-stage implementation of blockchain technology in the agricultural sector, particularly focusing on food traceability. Problems in current tracking technologies for agricultural supply chains are identified and blockchain technology is leveraged to ascertain how it could address these issues. Problems include centralised infrastructures leading to data integrity issues, lack of transparency and traceability in traditional logistic information systems, information asymmetry among stakeholders, and data format standardisation challenges.

Blockchain contributes to solving these issues by ensuring verified and validated data storage, preventing tampering through consensus mechanisms, eliminating the need for intermediaries, providing visibility of operations to network nodes, offering transparency to consumers, and establishing a common platform for all participants.

Despite advancements in food traceability, the paper identifies open research questions (ORQs) that present future challenges. ORQ-1 explores the economic and organisational impact of blockchain in real agricultural supply chains, emphasising the need for empirical data. ORQ-2 delves into the relationship between blockchain and the IoT in terms of data management, highlighting the need for further studies on the integration feasibility. ORQ-3 investigates the willingness of stakeholders to adopt public/permission-less blockchains, focusing on concerns about data openness and confidentiality. ORQ-4 addresses the truthfulness of data entered in the blockchain, emphasising the potential for fraudulent data, and proposing areas for further exploration, such as penalties for dishonest actors and the use of hardware cameras for image verification.

4.3.4. Conclusions

Current research trends are identified, significant issues that blockchain could solve in agricultural supply chains are addressed and future challenges or open research questions are outlined.

The three-step research methodology revealed a robust growth in blockchain technology, particularly in the agricultural sector, with a notable increase in scientific contributions in recent years. Despite this growth, the technology is in its early stage within the agricultural domain, lacking real case studies to demonstrate tangible benefits from economic and organisational perspectives.

The need to investigate stakeholders' inclination toward adopting blockchain technology and highlighted the ongoing effort required to enhance the credibility and reputation of blockchain in the agricultural sector is emphasised. The analysis of traceability-oriented keywords on Scopus revealed ten main articles proposing models for tracking and tracing agricultural supply chains using blockchain. These articles were reviewed based on the starting problem, area of interest, and contribution, noting that most were characterised by general concepts rather than specific real agricultural supply chains.

The research affirmed the promising nature of blockchain technology, with a surge in recent contributions indicating significant interest from the scientific community. The potential application of blockchain in agricultural supply chains could minimise fraud and errors, ultimately enhancing the quality and safety of food products. The study underlined the importance of further research, empirical case studies, and efforts to establish blockchain's credibility in the agricultural context.

4.4. Yan, Yang & Kim (2021)

4.4.1. Summary

The article discusses the growing consumer demand for safe and healthy agricultural products, particularly considering concerns about the authenticity of ecological organic products. With the prevalence of the Internet and increasing food safety incidents, there is a lack of trust in these products. The paper highlights the significance of traceability in the agricultural industry. The emergence of blockchain technology, known for its convenience, safety, decentralisation, and information security, is considered a solution to enhance trust in agricultural products.

The characteristics of blockchain, such as decentralisation, information immutability, openness, and autonomy, are identified as key factors driving its widespread adoption. The study reviews the historical development of agricultural traceability systems globally and proposes the integration of blockchain technology with these systems. Using qualitative research and case studies, the article analyses representative blockchain applications in agricultural traceability. Findings indicate that the application of blockchain and IoT technology in agricultural traceability has dual effects. The article offers recommendations for the application and development of blockchain technology in domestic agricultural traceability systems, aiming to contribute valuable insights for the comprehensive advancement of blockchain in the agricultural sector.

4.4.2. Background

The application of blockchain technology in agricultural product traceability systems is presented, providing an overview of blockchain as a distributed ledger. The article emphasises the importance of combining blockchain with agricultural traceability systems, citing advantages such as enhanced data entry, storage, protection, and query capabilities.

The challenges in the current agricultural product traceability system, including information asymmetry, operational inefficiency, low consumer trust, lack of standardisation, and vulnerability to fraud, are discussed. Blockchain's ability to address these issues by offering a decentralised, transparent, and secure platform for recording and managing agricultural product information is identified and the integration of blockchain and IoT technology is deemed crucial for establishing a transparent and accurate agricultural product data information database, facilitating quick access to supply chain information.

Complexities in the current agricultural traceability system are acknowledged (e.g., information asymmetry, inefficient operations, and low consumer trust). Blockchain technology can address these challenges by providing a decentralised, transparent, and secure platform for managing agricultural product information. The work suggests that the application of blockchain can improve information sharing, traceability, and transparency in the agricultural supply chain, benefitting consumers, producers, and regulatory authorities.

4.4.3. Practical applications

The practical applications of the research are evident in the implementation of blockchain technology in the agricultural sector, specifically in the traceability systems for agricultural products. Several companies and research institutions have undertaken projects and initiatives to leverage blockchain for enhancing the transparency, traceability, and integrity of data in the agricultural supply chain.

Provenance is recognised as the pioneer in using blockchain technology to provide full traceability for products in the supply chain. It tracks the entire life cycle of products, offering a comprehensive solution for supply chain transparency.

A study focused on a pilot project for tuna certification based on blockchain technology. The supply chain technology was used to achieve transparency and traceability of data information in the tuna supply chain, showcasing the adaptability of blockchain in different product contexts.

Ripe Technology integrates blockchain and IoT technology into its management system for crop tracking. The IoT is employed to monitor the entire process of crops from planting to sales, with blockchain ensuring detailed and tamper-proof records. SkuChain applies blockchain to track the entire circulation process of agricultural products, enhancing record-keeping and supervision in the product supply chain. The distributed accounting method ensures data integrity and transparency.

IBM collaborates with domestic and foreign research institutions, including Wal-Mart and Tsinghua University, to utilise blockchain for food traceability systems. The technology is employed to authenticate each product and maintain open and transparent product records within supermarkets.

Introduction of a blockchain double-chain structure, based on a "user information chain" and a "transaction chain" system, addressing key problems in the existing domestic public service platform. This dual-chain structure ensures openness, security, privacy, and efficiency in transaction information within the agricultural product supply chain.

The integration of blockchain into agricultural traceability systems brings various benefits, including improved data sharing, information security, and traceability. It addresses challenges in traditional traceability systems such as data storage costs, supervision costs, and operational efficiency, contributing to the stability and reliability of the domestic agricultural product market. Achieving source verification, traceability, accountability investigation, information visualisation, and big data management. Each product is uniquely identified, allowing consumers to access detailed information through scanning QR codes, thereby enhancing brand credibility. The research demonstrates the tangible impact of blockchain technology on improving the agricultural traceability system, fostering transparency, and building trust among consumers, producers, and regulatory authorities.

4.4.4. Conclusions

The research acknowledges the positive impact of blockchain technology on agricultural traceability but identifies existing challenges.

Current blockchain technology and applications are not fully mature. The work suggests increasing capital investment and research by national scientific research departments to address technical limitations such as insufficient capacity and slow processing speed. Participation from industrial enterprises and agricultural institutions in blockchain research and development is encouraged.

The need to accelerate the development of communication infrastructure in rural and western regions is emphasised. The work also advocates for the establishment of an Internet-based information platform to enhance agricultural informatisation and calls for financial support, policy guidance, and government coordination to facilitate the creation of a comprehensive network system.

The promotion of information technology, particularly blockchain, to grassroots agricultural practitioners through education, training, and regular programs is recommended. The work proposes improving their information knowledge, awareness, and confidence in blockchain applications. Interdisciplinary education to cultivate talents proficient in both information technology and agriculture is encouraged.

The judicial department is urged to formulate comprehensive laws and regulations concerning agricultural product safety traceability and blockchain applications. The work highlights the importance of preventing privacy leaks and emphasises the role of relevant agencies, such as the Ministry of Agriculture and Rural Affairs, in issuing timely guidance policies, white papers, and detailed documents.

State guidance and encouragement for the construction of blockchain industry standards is recommended. The work emphasises the participation of government departments, industry associations, companies, and organisations in developing these standards and highlights the potential of industry standards to promote industry development and reduce costs.

4.5. **Yang, Li, Yu, Wang, Xu & Sun** (2021)

4.5.1. Summary

This paper addresses the shortcomings of traditional traceability systems in agricultural product supply chains, such as centralised management, opaque information, untrustworthy data, and the creation of information islands. To overcome these issues, the authors propose a traceability system based on blockchain technology. Leveraging the decentralised, tamper-proof, and traceable nature of blockchain, the system enhances the transparency and credibility of traceability information. The design includes a dual storage structure for on-chain and off-chain traceability information, reducing the load on the blockchain and improving information query efficiency. The integration of blockchain and cryptography ensures secure sharing of private information within the network. A reputation-based smart contract is also introduced to incentivise network nodes to upload traceability data. The paper provides performance analysis and practical application results, demonstrating improved query efficiency, enhanced security of private information, and the authenticity and reliability of data in supply chain management, aligning with real-world application requirements.

4.5.2. Background

This challenges in the traceability of fruit and vegetable agricultural products are introduced, emphasising the short storage time and low storage temperature requirements that lead to food safety incidents. The importance of traceability in the food supply chain are highlighted and the enactment of relevant laws and regulations to address safety incidents. The concept of blockchain technology as a solution is promulgated, emphasising its decentralised, tamper-proof, and traceable nature. The discussion covers the subjects involved in fruit and vegetable agricultural product traceability, including internal and external entities of the supply chain. The limitations of traditional traceability systems, such as centralised management and data tampering, are discussed. The potential of blockchain technology, categorised into public chains, consortium chains, and private chains, is explored, with a focus on the consortium chain for its relevance to supply chain participants.

The application of blockchain technology to agricultural product traceability is detailed, including the design process and key breakthrough technologies of a traceability system. The system's features include on-chain and off-chain storage structures and the use of cryptography for privacy data protection.

4.5.3. Practical applications

The practical application of the traceability system involves a blockchain-based process for fruit and vegetable agricultural products. The traceability information is classified into private and public information. Private information undergoes encryption before being uploaded to the blockchain, while public information is stored in the local database and hashed with hash values stored in the blockchain system, and the block number updated in the corresponding database record. Consumers may verify the authenticity of products by scanning the QR code, comparing the hash value from the blockchain, and determining if the traceability information has been tampered with.

The system has been successfully applied to an apple company in China. The application includes designing a traceability method for the entire supply chain, using the dual storage design, and implementing an efficient storage and query system. Practical application examples include product labels, QR code scanning for traceability information, and data storage certificate information.

Costwise, the equipment and system software costs increased by 7.3% and 24.9%, respectively, compared to traditional traceability systems. The application involves renting multiple server equipment, and there are increased costs for system development, maintenance, and worker training. The use of IoT devices for automatic data upload, however, reduces human resource waste and lowers labour costs by 5.3%. An 18.2% increase is also recorded in the total cost of the product and a 34.6% increase in sales revenue between 2019 and 2020. While various factors contribute to the revenue increase, the application of the blockchain-based traceability system is believed to play a significant role in guaranteeing authenticity and may contribute to overall sales growth.

4.5.4. Conclusions

The paper focuses on designing and implementing a traceability system for fruits and vegetables agricultural products, leveraging the non-tampering and traceable characteristics of blockchain technology. Key challenges addressed include high data load pressure and inadequate private security, particularly pertinent to South Africa's agricultural landscape. As the system's data volume increases, these challenges may pose significant hurdles for effective implementation. The proposed solution introduces an innovative on-chain and off-chain data storage approach. Public information visible to consumers is stored in the local database of the supply chain, and its algorithm-generated hash value is uploaded to the blockchain system. Private information undergoes encryption and is stored directly in the blockchain for sharing with relevant companies. This dual storage approach is designed to balance the encryption needs of corporate private information with the requirement for public supervision of supply chain information, ultimately reducing data load pressure on the blockchain.

The exploration of multi-chain technology to meet evolving business needs is encouraged and the authors express their intention to delve into cross-chain technology between multiple chains and the development of a new consensus mechanism suitable for traceability applications.

4.6. **Demestichas, Peppes, Alexakis & Adamopoulou** (2020)

4.6.1. Summary

The paper explores the role of food in human societies globally, emphasising the complexity of the agricultural supply chain due to diverse stakeholders, including farmers, distributors, retailers, and consumers. This complexity poses challenges to achieving efficient transparency and traceability. The focus is on applying blockchain technologies to enhance traceability in the agri-food domain.

The paper reviews traceability, including definitions, adoption levels, tools, and advantages, along with a brief introduction to blockchain technology. A comprehensive literature review follows, examining the integration of blockchain into traceability systems. The authors then explore existing commercial applications, addressing challenges and discussing prospects for applying blockchain in the agri-food supply chain.

4.6.2. Background

The complexity of food supply chains is interrogated, attributing issues like lack of transparency and food safety concerns to this complexity. The impact of food epidemic incidents over the past two decades and the subsequent establishment of global directives, laws, and regulations to prevent such outbreaks are emphasised. The European Directive 178/2002 is highlighted as an example, making traceability of food products compulsory since 2005.

Consumer concerns regarding food provenance and quality are noted, leading to a willingness to spend more on certified products. Despite existing technologies, the paper argues that many traceability systems are centralised, asymmetric, and outdated in terms of data sharing and interoperability. This situation contributes to a lack of transparency and trust among consumers, necessitating innovative solutions.

The authors observe a surge in emerging technologies, such as blockchain, IoT, and distributed ledger technologies (DLT), as potential solutions to enhance traceability in the agricultural supply chain. The paper focuses on DLT like blockchain, acknowledging their promise but also recognising new challenges they pose.

The authors conduct an extensive literature review covering scientific papers, technical publications, research projects, and pilot platforms that leverage blockchain for traceability in agriculture supply chains, with the aim to provide a comprehensive analysis of research activities, offering a taxonomy and chronological presentation of studies. This compilation serves as a foundation for future research initiatives aimed at addressing the existing challenges in the domain of food traceability.

4.6.3. Practical applications

The practical applications of blockchain technology in agriculture traceability are varied and evolving. Early electronic traceability systems were centralised and based on databases. Centralised computing systems have been used in other traceability frameworks, including those based on printed tags with traceability codes. As the volume of data increase, databases can become heavily loaded, necessitating additional computational power.

Commercially, IBM Food Trust is a celebrated application that uses blockchain on the Hyperledger Fabric platform for tracing the provenance of products like mango and Chinese pork, significantly reducing the time required for tracking. Provenance is another company applying blockchain for traceability, uniquely tagging fish products to reduce certification costs and provide trustworthy information. Several startup companies are emerging in the blockchain-supported agri-food traceability space. For example, AgriOpenData aims to ensure transparent, secure, and public traceability of the entire agri-food chain, focusing on BIO and DOCG products, but challenges exist in the widespread adoption of blockchain in agriculture. Societal factors include low technological knowledge among stakeholders, the complexity of roles, and the distribution of the food supply chain across large geographical areas. Technical challenges involve data accuracy, monitoring, integration, and scalability, with many solutions tested in laboratory environments. Financial perspectives also raise concerns about the significant investment required for training personnel, obtaining equipment, and addressing high traceability costs.

Regulatory requirements, internal supply chain and production processes, and organisational changes pose more challenges. The role of governments in encouraging digitalisation, making investments in technology and education, and bridging the digital gap between developed and developing countries for successful adoption of emerging technologies like blockchain in agriculture is also explored.

4.6.4. Conclusions

This study investigates traceability techniques and blockchain technologies, particularly their combined application in the agriculture sector. It recognises the well-established field of traceability, marked by global regulations and laws governing agri-food product traceability. Blockchain technology's integration into agriculture traceability systems has gained prominence only in recent years, with a noticeable rise in startups and pilot applications.

The research suggests that employing blockchains can significantly enhance traceability by ensuring irreversible and immutable data storage. Blockchain technology establishes a credible and sustainable food industry, but the study acknowledges existing challenges, including regulatory considerations, stakeholder relationships, data ownership, and scalability, which need to be addressed for successful implementation.

To facilitate a better understanding of blockchain technology and potentially spur new implementations, the study proposes the development of a universal evaluation model. A successful system implementation in the agriculture sector should achieve cost reduction, risk mitigation, time savings, and increased trust and transparency. Stakeholders are more likely to adopt new methods if they find them user-friendly, productivity-enhancing, and value-adding. Introducing new technologies into the traditional agriculture sector is a substantial challenge that requires step-by-step implementation and active engagement with stakeholders across the supply chain.

4.7. **Xiong, Dalhaus, Wang & Huang** (2020)

4.7.1. Summary

Blockchain serves as a decentralised ledger in agriculture, providing a reliable and cost-effective source of truth for farms, inventories, and contracts. It enables transparent food supply chains, fostering trust between producers and consumers. Blockchain supports data-driven technologies for smarter farming and, when combined with smart contracts, facilitates timely payments triggered by blockchain-recorded data changes. This article explores blockchain applications in food supply chains, agricultural insurance, smart farming, and agricultural product transactions, addressing both theoretical concepts and practical perspectives. It also interrogates challenges related to recording transactions by smallholder farmers and establishing an ecosystem for widespread blockchain utilisation in the food and agriculture sector.

4.7.2. Background

The agriculture sector increasingly relies on data and information for improved productivity and sustainability. Information and Communication Technology (ICT) enhance data-related processes, allowing farmers to make informed decisions. ICT usage can, however, be influenced by biases and individual interests. Blockchain technology, as a decentralised ledger, addresses this issue by distributing data management power among several participants. Blockchain records information collaboratively through a peer-to-peer network, requiring verification by the majority before additions or alterations. This technology is considered transformative for agriculture, offering efficient, verifiable, and permanent transaction recording between parties with the potential to revolutionise data usage in the agricultural domain.

4.7.3. Practical applications

This research explores the practical applications of blockchain technology in the agricultural and food sectors, focusing on four key areas: agricultural insurance, smart farming, food supply chains, and transactions of agricultural products.

Blockchain technology is applied to enhance agricultural insurance, particularly in managing weather-related risks. Traditional indemnity-based insurances face challenges related to asymmetric information, adverse selection, and moral hazard. The research proposes using blockchain for index-based insurances, where payouts are triggered by measurable indices like rainfall. Smart contracts based on blockchain facilitate timely and automated payouts, reducing basis risk. Several companies are already working on smart index insurance contracts using blockchain.

The research emphasises the role of blockchain in establishing trust and security in smart agriculture, which involves utilising ICT, IoT, and various data collection technologies. Blockchain ensures transparency and immutability of data related to natural resources, supporting data-driven mobile applications for optimising farming. The joint application of IoT and blockchain is illustrated in smart agriculture models, where IoT sensors and blockchain contribute to data integrity and security.

Blockchain is employed to address common issues in food supply chains, such as traceability, safety, quality, and trust. The technology enables the recording of product information from its origin to the retail store in a secure and immutable way. This transparency helps in detecting issues like contamination or fraud. Various companies, including major retailers like Wal-Mart, Alibaba, and JD.com, are actively implementing blockchain for food traceability projects to enhance visibility and traceability in their supply chains.

The application of blockchain in the food supply chain aims to create trust relationships between producers and consumers. For producers, blockchain helps build product reputation through transparently providing individual product information. Consumers benefit from reliable information about food production, addressing concerns about safety and quality. Regulatory agencies also gain access to accurate information for informed and efficient regulations.

4.7.4. Conclusions

Blockchain technology enhances traceability in the food supply chain, promoting food safety and providing a secure framework for data storage and management. It facilitates data-driven innovations in smart farming and supports the implementation of smart index-based agricultural insurance. The technology can potentially reduce transaction costs, improving farmers' access to markets and creating new revenue streams. Certain limitations must be addressed for widespread adoption in the agriculture and food sectors, however.

Research is needed to understand the motivation of transacting parties, especially in the context of smallholder farming, to provide accurate information to the blockchain ledger. The scattered nature of information owned by individual farmers poses challenges, and future studies should assess which farms might benefit or face challenges with blockchain solutions. As these small holder farmers face some financial constraints, thus some solutions such as government subsidies, cooperative ventures, or partnerships with technology providers could inclusive could incentivise blockchain adoption and uphold traceability integrity in the agricultural sector.

Obtaining data for blockchain upload can be expensive, potentially hindering adoption. While the setup of a distributed ledger may be relatively inexpensive, the cost of collecting essential data, such as DNA of livestock animals, could be high. Sampling could reduce costs, but it requires a large population, raising concerns about increasing income discrepancies between larger and smaller farms.

Blockchain does not seamlessly integrate with existing legacy systems, requiring successful integration with databases and systems like enterprise resource planning, warehousing management, and manufacturing execution systems. Building the necessary infrastructure for blockchain implementation can be time-consuming, emphasising the importance of middleware and communication protocols to connect with existing systems.

4.8. **Patelli & Mandrioli** (2020)

4.8.1. Summary

The review highlights the increasing adoption of distributed ledgers, particularly blockchain, for tracing agrifood supply chains due to their attributes of safety, immutability, transparency, and scalability. The discussion focuses on relevant case studies showcasing the application of blockchain and other distributed ledger technologies in agrifood supply chain traceability. Acknowledging the diverse requirements of traceability in different supply chains, the review proposes a logical framework to aid in identifying the most suitable blockchain structure for each agrifood supply chain. This framework aims to facilitate the recognition of supply chains where intricate blockchain technologies may not be essential.

4.8.2. Background

In recent decades, heightened consumer awareness of food safety has led to increased demand for reliable certifications and traceability systems. Trust in the origin and quality of food has diminished, necessitating robust certification systems, particularly for local and organic products. BCTs emerge as potential solutions, offering trust-proof systems that enable secure and immutable records of transactions across entire supply chains. BCTs, originally designed for cryptocurrencies like Bitcoin, have gained popularity, evident in the growing number of scientific articles on the subject. The use of BCTs in agrifood supply chains has been explored since 2016, with an increasing focus on traceability applications. Notably, proof of concept projects in this domain has been reported in newspaper journals rather than scientific publications, hindering a comprehensive understanding of their outcomes.

4.8.3. Practical applications

"Trace My Egg" Project by Bytable was aimed at digital traceability of individual egg packs. Hyperledger Sawtooth was used as BCT technology, with codes stamped directly onto eggs leading to enhanced transparency and traceability in Aotearoa’s egg industry. Consumer interest and support for transparency and traceability was high.

Walmart's Case Studies applied traceability of pork meat and mango using IBM Food Trust Platform based on Hyperledger Fabric. This proved the versatility of BCTs, tracking up to 25 different products from five producers, and highlighted the potential application of BCTs across various agrifood supply chains.

IBM Food Trust used for Beefchain, a tool for meat origin traceability in case of disease outbreaks. This tool reduced traceability time, improving efficiency and food safety and it received USDA certification as a Process Verified Program.

The French company Carrefour implemented a BCT project like Walmart's which enabled traceability information sharing across the Auvergne chicken supply chain. It provided consumers with complete product traceability from farm to fork.

Ethereum's traceability project for coffee demonstrated adaptability to the food supply chain.

Amazon Web Services use Farmobile for BCT application in farming and agriculture.

AgriLedger, a system focused on digital identity, traceability, and immutable records using DLT which used its BC platform for Alpha Acid Brewery to enhance traceability for an artisanal beer producer. It hosted Certified Origins, a BC-based open ledger for Extra Virgin Olive Oil transparency.

An Irish project offering traceability for various food categories, emphasising raw material origin and which allows tracking of carbon footprint for some products, addressing consumer concerns about safety.

4.8.4. Conclusion

BCTs show proven potential for enhancing traceability in agrifood supply chains, demonstrated by recent articles and case studies. Despite ongoing studies resembling proofs of concept, BCTs are considered mature and robust technologies. Barriers and challenges hinder widespread adoption, however, including farmers' and food supply systems' lack of confidence due to insufficient knowledge about the cost and complexity differences among available BCTs. BCTs, though secure and reliable, require improved understanding of data storage and manipulation to address emerging challenges in data management. The adoption of BCTs could contribute to reducing the digital divide in farms and food supply systems, promoting the use of other emerging technologies for enhanced automation, transparency, and traceability. To encourage BCT adoption, future case studies should emphasise economic sustainability and project outcomes, while governments should support BCT integration in agrifood chains through policy measures and regulatory frameworks.

4.9. **Yao & Zhang** (2022)

4.9.1. Summary

The paper addresses issues with traditional centralised agricultural traceability systems, including low reliability, privacy vulnerabilities, and information islands. To overcome these challenges, the authors propose a trusted agricultural product traceability system based on the Ethereum blockchain. Traditional centralised systems may compromise reliability and privacy. The proposed solution leverages the Ethereum blockchain to establish a decentralised traceability system. A "Blockchain+IPFS" model is designed to alleviate storage pressure on the blockchain, ensuring efficient information queries while reducing the risk of information islands.

The paper suggests a privacy protection solution involving cryptographic primitives and the Merkle Tree, aimed at preventing leaks of sensitive enterprise data. The proposed system is implemented on the Ethereum blockchain, and the paper provides a thorough analysis of its cost, performance, and security. A comparison with existing solutions demonstrates the efficiency and feasibility of the proposed system.

4.9.2. Background

This paper addresses the challenges in the agricultural industry related to the safety, preservation, and traceability of agricultural products. Agricultural safety incidents jeopardise consumer trust, leading countries worldwide to enact laws emphasising product traceability. Traceability, crucial in the agricultural supply chain, involves recording key details from production to consumption. Existing centralised traceability systems face issues such as insecure data storage, low reliability, and privacy concerns.

The paper advocates for trusted traceability using blockchain technology, specifically Ethereum. Blockchain ensures data integrity, prevents tampering, and resolves trust issues in centralised supply chains, but faces challenges in transaction processing capacity and data privacy. To tackle these, the paper proposes an agricultural product traceability system based on Ethereum.

Possible solutions include combining blockchain with the IPFS to alleviate storage pressure, enhance query speed, and increase system flexibility. The leveraging of cryptographic primitives and the Merkle Tree to protect traceability information and prevent the disclosure of sensitive enterprise data may also be considered. The proposed system is implemented, tested, and analysed for cost, performance, and security. A comparison with existing systems is provided, and limitations are discussed.

The proposed Ethereum blockchain-based agricultural product traceability system aims to ensure security, traceability, immutability, and accessibility of data provenance while addressing storage and privacy challenges.

4.9.3. Practical applications

The research has several practical applications and is compared with traditional agricultural traceability systems and related works. Traditional systems are centralised, prone to failures and tampering whilst the proposed system is decentralised, enhancing reliability. Traditional systems use local databases, leading to data loss but the proposed dual storage model uses blockchain for key information and IPFS for traceability data, preventing loss and forming information islands.

Due to centralised management, traditional systems may face unauthorised changes and attacks. The proposed decentralised system ensures the reliability of traceability. Traditional systems are tedious to audit in case of safety incidents while the proposed system, based on blockchain, enables easy tracking and auditing of all participants.

The proposed system achieves trusted traceability throughout the supply chain, allowing consumers to verify product quality, a feature lacking in some references. The choice of Ethereum for the proposed system leverages its rich ecosystem, providing greater value compared to other platforms. The dual storage model, with off-chain storage on IPFS, addresses the data explosion issue of blockchain, distinguishing it from references storing all data on-chain.

The proposed system ensures privacy protection through cryptographic primitives and the Merkle Tree, a feature lacking in some related works. The proposed system is implemented on the Ethereum Mainnet, demonstrating feasibility, and providing a specific performance evaluation, setting it apart from other references. The main limitation is the potential rise in cost due to gas fees on the Ethereum Mainnet. Future research aims to address this by exploring low-cost permissioned blockchains with an improved PoA consensus algorithm. The proposed traceability system is less functional, and future research could integrate technologies like RFID and artificial intelligence for a more comprehensive and efficient system.

4.9.4. Conclusions

The paper addresses concerns over agricultural product safety by proposing a trusted traceability system. Traditional centralised systems suffer from security and reliability issues, prompting the use of blockchain technology for its tamper-proof and decentralised features. The paper focuses on challenges like storage, scalability, and privacy leakage in agricultural traceability systems, presenting an Ethereum Blockchain-based solution.

Agricultural safety incidents necessitate a traceability system to monitor the entire supply chain, enhancing safety and preventing problems. Traditional traceability systems face problems like insecure data storage, low reliability, and vulnerability to attacks. Blockchain, with its tamper-proof and decentralised nature, is considered promising for agricultural product traceability. The paper suggests an Ethereum Blockchain-based traceability system, addressing challenges of storage, scalability, and privacy leakage.

A model storing key information on-chain and traceability information off-chain is designed to alleviate storage pressure and enable efficient queries. The proposed system includes a solution to prevent sensitive enterprise data leakage in traceability information. The system is implemented, tested, and analysed for cost, performance, and security, demonstrating feasibility. The authors suggest optimising the consensus algorithm to improve system throughput and efficiency in future work.

4.10. **Bosona & Gebresenbet** (2023)

4.10.1. Summary

The text discusses the growing demand for a reliable and efficient traceability system in agri-food supply chains (AFSCs) due to concerns about food quality and safety. The current centralised traceability systems face challenges such as information loss and data tampering. To address these issues, there is an increasing focus on the application of BCT in AFSCs. The study reviews 78 relevant studies on the integration of BCT into traceability systems, emphasising the types of food traceability information and their application, particularly in fruit and vegetables, meat, dairy, and milk. BCT-based traceability systems are described as decentralised, immutable, transparent, and reliable, with the potential for real-time data monitoring and decision-making automation. The text also outlines key information providers, challenges, and benefits of BCT-based traceability systems, highlighting their positive impact on AFSC management, including reducing food loss, recall incidents, and contributing to United Nations Sustainable Development Goals (SDGs) such as 1, 3, 5, 9, and 12. The study aims to fill a knowledge gap and provide insights for academicians, managers, practitioners, and policymakers in the AFSCs.

4.10.2. Background

The text highlights the challenges faced by the agriculture industry, including the pressure to meet the demands of a growing global population for safe and high-quality agri-food products. The globalised food supply chain, with increased dependence on imported food, has raised concerns about food safety and quality. The complexity of agri-food supply chains, involving various actors and responsibilities, makes management and traceability challenging. Ineffectiveness in traceability systems can lead to economic losses and health issues due to food contamination and fraud.

Consumers demand a fast and trustworthy system to access information about food products, especially in the context of food safety issues like contamination and fraud. The text emphasises the need for comprehensive traceability systems, covering production, processing, and distribution, to address challenges such as food waste, counterfeiting, and fraudulent claims. It also discusses the role of Industry 4.0 technologies, including blockchain, in overcoming these challenges.

The importance of traceability in agri-food supply chains is discussed, with real-time information availability, safety, and reliability being crucial for efficiency. Blockchain technology as a solution to centralised traceability systems' problems is introduced, offering transparency and reliability. It mentions the challenges of implementing blockchain in complex supply chains and the potential benefits for real-time monitoring and decision-making.

The authors acknowledge the limited reviews on the application of blockchain in the agriculture sector, emphasising the need for more synthesis works, especially in BCT-based traceability for agricultural goods. It discusses the infancy of BCT-based traceability applications and the gaps in understanding data structure requirements and the potential impacts of such systems in agri-food supply chains. The paper aims to contribute to the development and application of effective BCT-based traceability systems in the agri-food sector by synthesising existing research results and introducing innovative concepts.

4.10.3. Practical applications

The research on BCT in AFSCs has several practical applications. BCT enables automation in AFSC management by supporting smart contracts triggered under pre-specified conditions. This reduces human interference, enhances efficiency, and lowers costs through automated processes supported by IoT sensors. BCT-based traceability systems can also significantly improve food recall processes. The manual and time-inefficient nature of current recall processes, which take about a week on average, can be automated using BCT. This can lead to quicker identification of contaminated products, mitigating health and economic crises associated with food contamination.

BCT enhances transparency in AFSCs, providing real-time information on food safety. Consumers with concerns about health risks show greater intention to purchase BCT-traceable food products, as it offers more information on product quality and safety. BCT-based traceability systems contribute to the reduction of food contamination and related recall incidents. This not only limits damage to consumer rights but also reduces food waste on retail and consumption levels, addressing the environmental impact associated with food waste.

The implementation of BCT-based traceability systems aligns with various United Nations SDGs. It supports economic sustainability by reducing costs and improving information sharing, environmental sustainability by managing resources effectively and reducing product loss, and social sustainability by addressing accountability, trust, food safety, and fraud prevention. BCT-based traceability systems help reduce food loss and waste by supporting efficient recall processes. By alerting all concerned actors throughout the supply chain immediately, BCT prevents food waste resulting from delayed recall processes.

BCT has the potential to bridge the digital divide in global food supply chains by making data collection and stakeholder interactions more efficient. Efforts are needed to support the application of BCT in developing countries, requiring digitalisation, training, education programs, and policy development. BCT-based traceability enables more sustainable consumption by reducing food loss and waste through efficient information flow. This supports consumers in making informed and efficient purchase decisions, contributing to SDG#12 (Sustainable Consumption and Production).

4.10.4. Conclusions

Despite the increasing research on BCT-based traceability systems in (AFSCs) since 2016, the practical application in real businesses is still in its early stages, especially in the context of global and complex supply chains. Further research is needed to design and implement effective BCT-based traceability systems for specific value chains within AFSCs. Existing traceability systems often use centralised databases with central servers, presenting challenges in transparency, trust, security, information availability, confidentiality, and auditability. In contrast, BCT-based systems offer advantages such as easy access to traceability data, immutability, decentralisation, transparency, scalability, and reliability. The automated nature of BCT-based traceability systems facilitates real-time data monitoring and decision-making.

The study maps out key types of traceability information, traceability information providers, challenges, and benefits across the entire AFSC, covering input supply, agricultural production, food processing, distribution, retailing, and consumption (including catering and restaurants). This comprehensive approach provides insights into the various stages of the supply chain where BCT-based traceability can be applied. BCT-based traceability systems have positive implications for AFSC management, including automation and improvement, reductions in food recall incidents through automated processes, and decreases in food loss and waste, leading to economic, nutrition, and resource savings. The study emphasises the alignment of BCT with the United Nations Sustainable Development Goals (SDGs) and its potential to bridge the digital divide, especially in low- and medium-income countries.

While BCT-based traceability systems offer solutions for issues like transparency, trust, and product traceability, they are not universally applicable to all complexities within AFSC management, particularly in long or global supply chains. The study is positioned to benefit academicians, managers, and practitioners in AFSCs by providing a comprehensive understanding of BCT and BCT-based traceability systems. The insights derived from the study aim to support the design, development, and implementation of these systems, contributing to the evolution of smart AFSCs.

4.11. **Mavilia & Pisani** (2022)

4.11.1. Summary

The article discusses the role of new (particularly blockchain) technologies, in the era of globalisation, highlighting the increasing attention from the academic and corporate sectors towards blockchain technology. The agricultural sector is identified as an area where data and information play a crucial role in enhancing productivity and sustainability, with Information and Communication Technology (ICT) playing a significant role in data management.

The article emphasises that blockchain technology, with its attributes of immutability and decentralisation, has applications in various sectors, including agriculture. It points out that the agricultural sector faces multiple challenges, such as population growth, climate change, biodiversity loss, and parasite spread, and emphasises the need for innovation to make agriculture profitable for both small- and large-scale farmers. The article discusses how emerging technologies like blockchain, IoT, drones, Big Data, and artificial intelligence can be used to improve agricultural production and distribution processes, but it also cautions that assessing the feasibility of implementing these technologies should consider their costs and potential risks.

A process for evaluating whether a blockchain-based solution is suitable for a particular agricultural process is outlined. Such a process might involve identifying use cases, understanding the fundamental process guidelines, including regulatory requirements, stakeholders, legal frameworks, interoperability, and selecting the appropriate technology to address the specific challenges. The article's scope is established as a review of the main applications of blockchain technology in the agricultural sector, with a focus on South Africa, recognising the significant potential of blockchain in transforming agriculture in the region.

4.11.2. Background

The literature review traces the origins of blockchain technology back to the publication which introduced Bitcoin to the market (Nakamoto, 2008) and the concept of blockchain, described as a distributed ledger technology (DLT) that acts as an immutable and incorruptible repository of information and a digital platform that records and verifies all transactions between users on a network.

The review then highlights three conceptualisations of blockchain technology:

- **Technical perspective**: Blockchain is described as a database distributed among users, openly inspectable, and synchronised across multiple computers in real-time.
- **Business perspective**: It is presented as a network where transactions and exchanges of value or goods can occur without the need for central intermediaries.
- **Legal perspective**: Blockchain is discussed as a technology that validates transactions, replacing traditional centralised entities.

The key components of a blockchain, including block number, stored data or transactions, hash values of previous and current blocks, and a nonce (a cryptographic value), are explained. The review underscores the security aspect of blockchain, particularly the use of cryptographic techniques, such as the SHA256 hash, which makes it extremely difficult to tamper with data once they are added to the blockchain.

The literature review also mentions the current prominent applications of blockchain technology, primarily in the financial sector, as well as its potential in various other domains such as insurance, data protection, intellectual property, electronic voting, identity verification, government services, healthcare, and social impact initiatives.

The research questions addressed in the paper focus on the potential applications of blockchain in the agricultural sector, especially in South Africa. The questions revolve around identifying key blockchain applications in agriculture and understanding the socio-economic characteristics of the South African agricultural sector. The review explores limitations and challenges from user perspectives (farmers) and the government, followed by policy recommendations.

4.11.3. Practical applications

Various applications of blockchain technology in the agricultural sector are examined. The review of the literature and practical cases highlights the following key points:

Emergence of blockchain in agriculture: The use of blockchain technology in agriculture began to gain attention in 2016, and it received increasing interest in 2019, with countries like India, China, and the USA leading in research on blockchain applications in the food and agriculture industry.

Drivers for adoption: The growing interest in blockchain technology in agriculture is driven by concerns related to food safety, data security, trust in financial transactions within the agricultural supply chain, and the need for transparency and integrity in agriculture data.

Agricultural supply chains: Blockchain technology is considered suitable for addressing inefficiencies in agricultural supply chains. It can provide a transparent and immutable platform for sharing information among stakeholders in the agri-food supply chain, potentially reducing operational costs.

Traceability and quality standards: Blockchain's ability to provide traceability in agricultural supply chains is emphasised. It can help track the origin and authenticity of agricultural products, ensuring food safety and quality. This transparency can also aid in regulatory compliance and fraud prevention.

Financial services for agriculture: Blockchain offers several advantages in the financial services sector for agriculture, through cost reduction, diminishing risks for sellers and banks, enhancing efficiency in supply chain financing, and facilitating digital payment services, which are faster and more secure than cash-based transactions.

Smart contracts and commercial finance: Blockchain's use of smart contracts is highlighted, enabling real-time payment settlements based on delivery and available funds. This can streamline entrepreneurial collaboration within smart rural supply chains.

Digital payment services: Blockchain-based digital payment services are mentioned to reduce costs and risks associated with cash-based transactions in the agricultural value chain. Platforms such as AgriLedger and FarmShare enable farmers to transact using cryptocurrencies.

Agricultural insurance: Blockchain can digitise and automate agricultural insurance payments using smart contracts, potentially expanding coverage, and simplifying claims processing. Platforms such as Etherisc offer insurance solutions for growers in developing countries.

Credit services: Blockchain technology provides financial institutions with access to data on the financial activities of farmers and value chain participants, enabling the provision of credit services. Start-ups like Everex offer small loans in developing countries through smart contracts, reducing costs, and improving lending conditions.

Agricultural derivatives: Blockchain can be applied in agricultural derivatives markets as a risk management tool to cover price risk and establish future prices for agricultural produce.

Land registry: Blockchain technology can address the shortcomings of traditional land registries, particularly in emerging countries where land transactions are susceptible to fraud. Blockchain-based land registries can offer secure, fast, and immutable methods for registering land titles, promoting trust in the system. Platforms like BenBen Ghana provide solutions for capturing transactions and verifying land ownership data through blockchain, enabling the use of smart contracts to ensure the accuracy of land records.

4.11.4. Analysis of the South African agricultural sector

South Africa's economic development: South Africa is the most developed country on the African continent. Its strategic location and economic infrastructure make it a significant operational base, not only as a market itself but also as a hub for the wider sub-Saharan region in terms of commerce and production partnerships.

Economic transformation: Following the end of apartheid, South Africa has undergone a significant economic transformation, shifting from a primary sector-based economy to one where services and manufacturing have gained prominence. Agriculture, while contributing to the country's GDP, accounts for a relatively small percentage (2.8%) of the economy compared to services and manufacturing.

Historical context: The article acknowledges that South Africa's agricultural sector and the agrarian reform issue are deeply intertwined with its colonial history and the legacy of the apartheid regime.

Role of agri-food industry: The agri-food industry in South Africa (25% of the manufacturing sector) is noted for its production of high-quality goods with competitiveness in international markets. Collaboration agreements with foreign companies have allowed South African farms to access technology and expertise, improving their competitiveness globally.

Key agricultural productions: Primary South African agricultural productions are:

- *Fruit Growing*: South Africa's diverse climate allows for the cultivation of various fruit species. Citrus fruits, especially oranges, are the most significant export item.
- *Wine Production*: South Africa is the eighth-largest wine producer globally, with a significant percentage of the world's wine production. The vineyards occupy extensive areas, mainly in the Western Cape and Northern Cape.
- *Corn*: South Africa is one of the world's major corn producers, primarily in the "Corn triangle" region, where other crops like peanuts, sunflowers, cotton, and cork are also grown.

Blockchain use case for food tracking in South Africa: The article introduces a pilot project called 'Blockchain for Agrifood' aimed at tracking grapes through blockchain technology in South Africa. This project was launched in 2017 and involves collaboration among several organisations. The primary objective of the 'Blockchain for Agrifood' project is to explore the applications of blockchain technology in the agri-food sector. It seeks to understand the relevance of blockchain, its real-world applicability, and its potential impacts and it aims to create and implement a proof of concept using South African table grapes as a case study.

Blockchain in grape supply chain: The pilot project focuses on the grape supply chain, particularly for organic grapes produced on a South African farm. It aims to use blockchain to address several aspects, including:

- *Origin Tracking*: Trace the origin of grapes from the producer to the buyer.

- *Certificate Issuance and Validation*: Certification authorities issue and validate certificates for products, with all certificates stored on the blockchain for transparency.
- *Auditing Certificates*: Audit organisations can revoke certificates in case of fraud or unethical behaviour, with audit results recorded on the blockchain.
- *Ownership Changes*: The blockchain records changes in ownership as grapes move through the supply chain.

Benefits of blockchain in agriculture: The article highlights how blockchain technology can mitigate counterparty risks in agricultural transactions, ensure secure payments, and provide the traceability and transparency needed in agricultural value chains.

4.11.5. Conclusions

The limitations and potential policy applications associated with the digitalisation of the agricultural sector, particularly using blockchain technology include:

- *Limitations*

Complexity of Blockchain: Blockchain technology, while promising, is considered complex and still in its early stages of development. Its complexity makes it challenging to apply effectively in various sectors, including agriculture.

Skill and knowledge gap: Users, including farmers, need to acquire the necessary skills and knowledge to implement blockchain applications effectively. Many individuals in the agricultural sector are unfamiliar with smart agriculture and lack the skills required for blockchain technology adoption.

Partnerships required: Successful implementation of blockchain technology in agriculture often necessitates partnerships with service providers specialising in blockchain-related solutions. Secure and shareable data platforms based on smart and decentralised contracts are required to achieve product traceability and transparency.

- *Policy Applications*

Promoting blockchain ecosystems: Policymakers can encourage the growth of blockchain ecosystems within agricultural chains. This support can help optimise competitiveness and sustainability within the agricultural supply chain.

Regulatory framework: Designing a regulatory framework specific to blockchain applications in the agri-food sector is crucial. This framework should address issues related to product traceability and process transparency.

Coordination and collaboration: Improved coordination among various stakeholders is essential to prevent resource wastage and missed opportunities in both the business and government sectors. Collaboration and testing of different blockchain solutions can contribute to technology maturity.

Governance and organisational focus: Policymakers should emphasise governance and organisational aspects, including collaboration, digitisation, and data standardisation. These aspects, along with complementary technologies like big data analysis, are crucial for successful blockchain implementation.

Public investment in research and development (R&D): Public investment in R&D can highlight the added value of blockchain applications. Funding research and development efforts can help identify the full potential of blockchain in agriculture.

The potential of new technologies, particularly Blockchain, in transforming the agricultural sector are considerable.

Blockchain's transformative potential: Blockchain technology has the potential to reshape the entire agricultural sector, contributing to the resolution of food crises by creating trust within value chains and ensuring transparency and sustainability. It is a powerful tool for improving agricultural processes.

Ongoing challenges: Despite its promise, Blockchain adoption in agriculture faces several challenges, both technical and non-technical. These challenges include the need for real-time and accurate information, more efficient global coordination among stakeholders, and streamlined bureaucratic procedures, as exemplified by lessons from the COVID-19-related global food supply chain disruptions.

Future research: Further research to overcome these challenges and fully harness the potential of Blockchain technology in agriculture is important. Future investigations will aim to find solutions to the existing obstacles and determine the most effective ways to implement Blockchain technology in the agricultural sector to realise its significant benefits.

5. ANALYSIS AND DISCUSSION

Contemporary agricultural and food markets exhibit a pronounced level of vertical coordination and integration, with multinational corporations and companies exerting significant dominance. The liberalisation of the South African food industry has led to heightened competitive pressures and an amplified emphasis on economies of scale (Swinnen & Maertens, 2007). The contrast between traditional and modern agri-food markets is stark in the present landscape. Several factors set these two markets apart, including specialised logistics and centralised sourcing for improved supply reliability in terms of quality and quantity. Key drivers of vertical integration encompass product traceability, quality, and food safety. The private standard also holds a central position, accompanied by the proliferation of formalised contracts and a growing emphasis on Corporate Social Responsibility (CSR) (Borsellino et al., 2020). The evolution from traditional to modern agri-food supply chains has introduced heightened complexity into the industry.

Blockchain technology has found applications across various sectors such as healthcare, banking, insurance, and supply chain management. During the implementation phase, frameworks play a crucial role in tailoring solutions to meet the specific needs and requirements of customers. These frameworks comprise coded software components that establish structure and functionalities, serving as a foundation for the customisation of larger software packages. This approach alleviates the need for developers to commence projects from scratch. The customisation of frameworks extends to the creation of new blockchain network integrations, incorporating advanced technologies and information input systems. Table 1 provides an overview of the examined concepts.

In the ever-expanding global marketplace, where products, information, and people seamlessly traverse international borders, consumers relish the diverse array of food products available in their local markets. The globalisation of the food sector, however, presents a dual challenge: ensuring food safety amid increasingly intricate and globally intertwined supply chains. As consumers enjoy the convenience of accessing food from around the world, it has become imperative to guarantee the safety, quality, and sustainability of these products.

The demand for full traceability of individual ingredients in end products has emerged as a fundamental requirement for quality assurance. This necessity stems from the globalisation of food supply chains, with an increasing number of actors participating in the production, distribution, and sale of food products. Achieving traceability, the ability to track and trace the journey of each ingredient from its origin to the final product, is crucial to meeting the escalating demands of consumers for safety, quality, and sustainability.

The urgency for traceability is accentuated by past food scandals that have reverberated globally. Notable among these is the 2008 Melamine milk powder scandal in China. This tragedy, linked to contaminated infant milk powder, resulted in the loss of infant lives, imprisonment of business managers, market deterioration, and the bankruptcy of the milk powder supplier (Pei et al., 2011). Such incidents underscore the critical need for effective traceability systems to identify and rectify food safety crises promptly.

Table 1: List of research studies presenting different blockchain models.

Source/authors	Title
Basnayake and Rajapakse (2019)	A Blockchain-based decentralised system to ensure the transparency of organic food supply chain
Madumidha et al. (2019)	A theoretical implementation: Agriculture-food supply chain management using blockchain technology
Chopra (2020)	Blockchain technology in food industry ecosystem
Shahid et al. (2020)	Blockchain-based agrifood supply chain
Leng et al. (2018)	Research on agricultural supply chain system with double chain architecture based on blockchain technology
Chen, Li, and Li (2020)	Electronic agriculture, blockchain and digital agricultural democratisation: Origin, theory, and application
Hussain Awan et al. (2019)	Role of IoT with blockchain technology for the development of smart farming
Safak et al. (2019)	Hybrid database design combination of blockchain and central database

Consumer awareness has risen in response to these incidents, driving an increased emphasis on traceability as a linchpin of food safety. Consumers now view traceability not merely as a feature but as an essential component that influences their purchasing decisions. Transparent information about the provenance and journey of food products has become a key factor shaping consumer confidence and satisfaction.

The literature reflects a diversity of definitions for 'traceability,' indicating a lack of a universal understanding. However, for the purpose of this study, traceability is defined as an integral part of logistics management. This definition aligns traceability activities with logistics operations, emphasising the interconnectedness of efficiency and effectiveness in ensuring safety and quality control. Amidst these developments, blockchain technology emerges as a transformative solution for enhancing food traceability. Originally designed for digital currencies like Bitcoin, blockchain's unique features, including immutability, transparency, and decentralised control, position it as an ideal candidate for supply chain applications. Blockchain's potential lies in facilitating secure and transparent transactions, allowing seamless data exchange between supply chain partners.

This potential is, however, not without its challenges. Transaction rate limitations, concerns about protecting sensitive information, and potential vulnerabilities in the underlying programming code need careful consideration. Issues related to smart contracts and the necessity for standardised architectures supporting multiple supply chain processes and actors must be addressed to fully harness the revolutionary capabilities of blockchain in the food supply chain.

Blockchain technology has emerged as a prospective solution for establishing a robust food traceability framework. However, the feasibility of implementing such a framework is contingent upon the establishment of well-organised and standardised supply chains involving all actors, both internal and external. This study explores previous works done on the potential of blockchain technology to enhance food traceability frameworks. While acknowledging its promise, there is a necessity to define governance structures surrounding blockchain types and data standardisation before initiating the automation of processes. The pivotal factor is not solely the technology itself, but rather the standardisation of both internal and external traceability processes. This requires substantial organisational changes and the standardisation of master data among supply chain participants. The achievement of a transparent traceability level, benefiting all stakeholders, including consumers, is contingent upon overcoming these critical constraints. Data governance plays a pivotal role, ensuring consistent data definitions and defining authorities for data creation, access, and modification.

As blockchain technology continues to emerge, many countries face challenges in establishing comprehensive government regulations. Even when regulations are in place, variations in privacy standards, data storage practices, and registration procedures pose obstacles to achieving a standardised blockchain design. This complexity is particularly challenging for internationally oriented agricultural supply chains. Moreover, determining the implementation costs of blockchain networks is a difficult task, which may deter risk-averse agricultural entities with limited financial capabilities from adoption. The uncertainties surrounding blockchain implementation create additional barriers for organisations considering joining the network.

For successful blockchain adoption, stakeholders and users must undergo training and education. While the agricultural sector boasts high-level knowledge in cultivating quality plant-based products, industry professionals often lack technological expertise, especially in cutting-edge technologies and modern software systems. Limited educational resources further complicate the task of adequately training all stakeholders. Cultural shifts within the industry are also required to accommodate the changes brought about by blockchain technology.

During the implementation phase, a technical challenge arises in making blockchain technology interoperable with other information input systems and technologies. Blockchain, serving as a distributed ledger, relies on external applications for data input, demanding an interoperable infrastructure to link diverse systems. The ongoing discussion about the interoperability of systems intensifies when dealing with internationally oriented agricultural supply chains, given the multitude of software formats and languages used by various organisations.

Despite presenting numerous advantages for agricultural supply chains, blockchain technology encounters several challenges. The benefits include enhanced data security through a consensus mechanism that requires validation by at least 50% of all nodes. Blockchain's decentralised nature ensures data availability, expanding visibility and transparency within specified blockchain protocol limits. This, in turn, leads to shorter response times and quicker action in response to supply chain events. The consensus mechanism also reduces the risk of data tampering, and encrypted data storage with authentic signatures decreases the likelihood of data corruption. Blockchain adoption fosters trust among supply chain parties, facilitated using smart contracts that eliminate the need for intermediaries. This results in cost savings, reduced processing times, and potentially fairer pricing of products. However, the maturity of the system remains a question, as issues arise with data entry methods. Deterministic data entry minimises the risk of corruption, but the automated acceptance of data in blockchain-enabled systems, combined with the exclusion of third-party intermediaries, poses a threat to institutional knowledge within the industry.

Implementation of a blockchain network entails significant investment, operational, and maintenance costs. Empirical data on industry-wide implementation costs are lacking, contributing to uncertainties and hesitancy among entities considering joining the network. Technical challenges, such as low storage capacity, low throughput rate, high latency, and the trinity issue, further complicate the adoption of blockchain technology. Balancing scalability, security, and decentralisation proves challenging, with the chosen blockchain protocol and consensus mechanism influencing the energy consumption of the system, raising concerns about sustainability in the absence of large-scale implementations.

Data governance cannot be unilaterally determined by participants within a single blockchain initiative. Instead, it necessitates sector-wide, if not industry-wide, consensus to avoid the inefficiency of suppliers complying with disparate interface standards. To address this, the authors advocate for the establishment of consortia within business sectors, with support from governmental institutions. These consortia would play a crucial role in defining and driving standardisation efforts.

Standardisation and data governance serve as indispensable preconditions for progressing from blockchain pilots to enduring blockchain implementations. Although the standardisation process may extend over several years, it does not preclude the immediate use of BCT for food traceability. Recognising the growing consumer demand for transparency regarding ingredient origins, the short-term adoption of diverse solutions, including BCT, becomes imperative. Even if boundary conditions are only harmonised among a subset of supply chain actors, this could potentially enhance transparency for consumers and contribute to a reduction in food safety incidents.

6. CONCLUSION, IMPLICATIONS, RECOMMENDATIONS

Blockchain technology enhances transparency throughout the food supply chain by providing an immutable and decentralised ledger. This transparency fosters accountability among stakeholders, including farmers, producers, distributors, and retailers. The ability of blockchain to create a tamper-proof record facilitates quick and accurate traceability in the event of contamination or foodborne illnesses. This feature contributes to improved food safety and quality assurance, critical factors in safeguarding public health. It is also essential to acknowledge the unique challenges and considerations specific to South Africa’s agricultural landscape.

Implementing blockchain in food traceability builds trust and confidence among consumers. With access to transparent and real-time information about the origin and journey of food products, consumers can make informed choices, supporting businesses that prioritise safety and ethical practices. Blockchain technology streamlines the recall process in case of contaminated or unsafe products. The decentralised and immutable nature of the blockchain ledger allows for quick identification and isolation of affected products, minimising the impact on both consumers and the broader supply chain.

The integration of blockchain with other technologies, such as the IoT, enables real-time monitoring of environmental conditions during transportation and storage. This optimisation contributes to better inventory management, reduced waste, and overall efficiency improvements in the supply chain. The research underscores challenges in implementing blockchain technology, including scalability issues, energy consumption concerns, and the need for interoperability. The ongoing electricity crisis in South Africa presents a significant hurdle to the maintenance and development of blockchain infrastructure. Without reliable electricity supply, the implementation of blockchain solutions may face disruptions and operational challenges, hindering their effectiveness. South Africa's agricultural sector is characterised by high labour intensity and relatively low labour costs. In such an environment, the incentive to adopt complex technological tools like blockchain may be reduced, particularly among smallholder farmers who may lack the resources and expertise to implement and maintain these systems.

The regulatory framework for blockchain in food traceability is still evolving. Policymakers in South Africa should consider the development of clear and supportive regulations that encourage innovation while ensuring compliance with industry standards. Collaboration between the government and industry stakeholders is essential to create a conducive regulatory environment. Establishing standardised protocols and ensuring interoperability between different blockchain platforms is vital. Research suggests that a lack of standardisation may hinder the widespread adoption of blockchain in the food sector. South Africa should actively participate in international efforts to develop industry-wide standards.

Successful implementation of blockchain in South Africa requires an understanding of local agricultural and supply chain practices. Researchers and industry practitioners should tailor solutions to align with the unique characteristics of South Africa's food ecosystem, considering factors such as small-scale farming, diverse agricultural practices, and regional variations. The agriculture sector in South Africa is predominantly low-skilled in many areas, posing an additional challenge to the adoption of sophisticated technologies. It is likely that corporations and large players will be the primary drivers of blockchain solutions in the agricultural sector, further widening the gap between large-scale producers and smallholder farmers.

Despite these challenges, the potential benefits of blockchain technology in enhancing food traceability and safety cannot be overlooked. However, addressing these barriers to adoption will require concerted efforts from government, industry stakeholders, and the research community. Efforts should be made to tailor blockchain solutions to align with the unique characteristics of South Africa's food ecosystem.

Blockchain technology holds promise for improving food traceability and safety in South Africa, it is crucial to address the challenges specific to the local context to ensure the successful implementation and widespread adoption of these solutions. Ongoing research, collaboration, and innovation are key to overcoming these barriers and unlocking the full potential of blockchain in the South African agricultural sector.

7. REFERENCES

Arizona House Bill 2417, (2017).

Aung, M. M., & Chang, Y. S. (2014). Traceability in a food supply chain: Safety and quality perspectives. *Food Control*, *39*(1), 172–184. https://doi.org/10.1016/J.FOODCONT.2013.11.007

Bader, L., Burger, J. C., Matzutt, R., & Wehrle, K. (2018). Smart Contract-Based Car Insurance Policies. *2018 IEEE Globecom Workshops, GC Wkshps 2018 - Proceedings*. https://doi.org/10.1109/GLOCOMW.2018.8644136

Banerjee, R., Menon, H., & Ramful, K. (n.d.). Traceability in food and agricultural products. *International Trade Center*.

Barnett, B. J., & Mahul, O. (2007). Weather index insurance for agriculture and rural areas in lower-income countries. *American Journal of Agricultural Economics*, *89*(5), 1241–1247. https://doi.org/10.1111/J.1467-8276.2007.01091.X

Basnayake, B. M. A. L., & Rajapakse, C. (2019). A Blockchain-based decentralized system to ensure the transparency of organic food supply chain. *2019 International Research Conference on Smart Computing and Systems Engineering (SCSE)*, 103–107. https://doi.org/10.23919/SCSE.2019.8842690

Borsellino, V., Schimmenti, E., & El Bilali, H. (2020). Agri-Food Markets towards Sustainable Patterns. *Sustainability*, *12*(6), 2193. https://doi.org/10.3390/su12062193

Bosona, T., & Gebresenbet, G. (2013). Food traceability as an integral part of logistics management in food and agricultural supply chain. *Food Control*, *33*(1), 32-48. https://doi.org/10.1016/j.foodcont.2013.02.004

Bosona, T., & Gebresenbet, G. (2023). The role of blockchain technology in promoting traceability systems in agri-food production and supply chains. *Sensors*, *23*(11), 5342. https://doi.org/10.3390/s23115342

Buterin, V. (2017, February 6). The meaning of decentralization. *Medium*. https://medium.com/@VitalikButerin/the-meaning-of-decentralization-a0c92b76a274

Caro, M. P., Ali, M. S., Vecchio, M., & Giaffreda, R. (2018). Blockchain-based traceability in agri-food supply chain management: A practical implementation. *2018 IoT Vertical and Topical Summit on Agriculture - Tuscany, IOT Tuscany 2018*, 1–4. https://doi.org/10.1109/IOT-TUSCANY.2018.8373021

Chang, S. E., Chen, Y. C., & Lu, M. F. (2019). Supply chain re-engineering using blockchain technology: A case of smart contract-based tracking process. *Technological Forecasting and Social Change*, *144*, 1–11. https://doi.org/10.1016/J.TECHFORE.2019.03.015

Chen, Y., Li, Y., & Li, C. (2020). Electronic agriculture, blockchain and digital agricultural democratization: Origin, theory and application. *Journal of Cleaner Production*, *268*, 122071. https://doi.org/10.1016/j.jclepro.2020.122071

Chopra, A. (2020). Blockchain technology in food industry ecosystem. *IOP Conference Series: Materials Science and Engineering*, *872*(1), 012005. https://doi.org/10.1088/1757-899X/872/1/012005

de Caria, R. (2019). Definitions of Smart Contracts. In L. A. DiMatteo, M. Cannarsa, & C. Poncibò (Eds.), *The Cambridge handbook of smart contracts, blockchain technology and digital platforms* (pp. 19–36). Cambridge University Press. https://doi.org/10.1017/9781108592239.002

Demestichas, K., Peppes, N., Alexakis, T., & Adamopoulou, E. (2020). Blockchain in agriculture traceability systems: A review. *Applied Sciences 2020*, *10*(12), 4113. https://-doi.org/10.3390/APP10124113

du Plooy-Cilliers, F., Davis, C., & Bezuidenhout, R. M. (2014). *Research matters*. Juta.

Dujak, D., & Sajter, D. (2019). *Blockchain Applications in Supply Chain*. In A. Kawa, & A. Maryniak (Eds.), *SMART supply network* (pp. 21–46). https://doi.org/10.1007/978-3-319-91668-2_2

Esquirol-Caussa, J., & Sanchez-Aldeguer, J. (2017). *A bibliographical review: the basis of our research*.

Feng, H., Wang, X., Duan, Y., Zhang, J., & Zhang, X. (2020). Applying blockchain technology to improve agri-food traceability: A review of development methods, benefits and challenges. *Journal of Cleaner Production*, *260*, 121031. https://doi.org/10.1016/J.JCLEPRO.2020.121031

Finger, R., Dalhaus, T., Allendorf, J., & Hirsch, S. (2018). Determinants of downside risk exposure of dairy farms. *European Review of Agricultural Economics*, *45*(4), 641–674. https://doi.org/10.1093/ERAE/JBY012

Gatteschi, V., Lamberti, F., Demartini, C., Pranteda, C., & Santamaría, V. (2018). Blockchain and smart contracts for insurance: Is the technology mature enough? *Future Internet*, *10*(2). https://doi.org/10.3390/FI10020020

GFSI. (2022). *GFSI science technology advisory group report*. https://mygfsi.com/wp-content/uploads/2022/11/GFSI-STAG-2022-Report-Final.pdf

Golan, E., Krissoff, B., Kuchler, F., Calvin, L., Nelson, K., & Price, G. (2004). *Traceability in the U.S. food supply: Economic theory and industry studies*. www.ers.usda.gov.

Hasan, H. R., Salah, K., Jayaraman, R., Ahmad, R. W., Yaqoob, I., & Omar, M. (2020). Blockchain-based solution for the traceability of spare parts in manufacturing. *IEEE Access*, *8*, 100308–100322. https://doi.org/10.1109/ACCESS.2020.2998159

Hussain Awan, S. (2019). Role of internet of things (IoT) with blockchain technology for the development of smart farming. *Journal of Mechanics of Continua and Mathematical Sciences*, *14*(5). https://doi.org/10.26782/jmcms.2019.10.00014

Jha, S., Andre, B., & Jha, O. (2018). *ARBOL: Smart contract weather risk protection for agriculture*. https://www.arbolmarket.com/wp- content/uploads/2018/09/ARBOL_WP-1.pdf

Just, R. E., Calvin, L., & Quiggin, J. (1999). Adverse Selection in Crop Insurance: Actuarial and Asymmetric Information Incentives. *American journal of agricultural economics*, *81*(4), 834–849. https://doi.org/10.2307/1244328

Kamilaris, A., Fonts, A., & Prenafeta-Boldύ, F. X. (2019). The rise of blockchain technology in agriculture and food supply chains. *Trends in Food Science & Technology*, *91*, 640–652. https://doi.org/10.1016/J.TIFS.2019.07.034

Kelepouris, T., Pramatari, K., & Doukidis, G. (2007). *RFID-enabled traceability in the food supply chain*. https://doi.org/10.1108/02635570710723804

Kim, M., Hilton, B., Burks, Z., & Reyes, J. (2018). Integrating blockchain, smart contract-tokens, and IoT to design a food traceability solution. *2018 IEEE 9th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON)*, 335–340. https://doi.org/10.1109/IEMCON.2018.8615007

Leng, K., Bi, Y., Jing, L., Fu, H.-C., & Van Nieuwenhuyse, I. (2018). Research on agricultural supply chain system with double chain architecture based on blockchain technology. *Future Generation Computer Systems*, *86*, 641–649. https://doi.org/10.1016/j.future.2018.04.061

Lesk, C., Rowhani, P., & Ramankutty, N. (2016). Influence of extreme weather disasters on global crop production. *Nature*, *529*(7584), 84–87. https://doi.org/10.1038/nature16467

Lin, W., Huang, X., Fang, H., Wang, V., Hua, Y., Wang, J., Yin, H., Yi, D., & Yau, L. (2020). Blockchain technology in current agricultural systems: From techniques to applications. *IEEE Access*, *8*, 143920–143937. https://doi.org/10.1109/ACCESS.2020.3014522

Lin, Y.-P., Petway, J. R., Anthony, J., Mukhtar, H., Liao, S.-W., Chou, C.-F., & Ho, Y.-F. (2017). Blockchain: The evolutionary next step for ICT e-agriculture. *Environments*, *4*(3), 50. https://doi.org/10.3390/environments4030050

Lobell, D. B., Schlenker, W., & Costa-Roberts, J. (2011). Climate trends and global crop production since 1980. *Science*, *333*(6042), 616–620. https://doi.org/10.1126/science.1204531

Lucena, P., Binotto, A. P. D., Momo, F. da S., & Kim, H. (2018). *A case study for grain quality assurance tracking based on a blockchain business network. Proceedings of the Symposium on Foundations and Applications of Blockchain (FAB 18) March 9, 2018, Los Angeles, California, USA.* https://arxiv.org/abs/1803.07877

Madumidha, S., Ranjani, P. S., Vandhana, U., & Venmuhilan, B. (2019). A theoretical implementation: Agriculture-food supply chain management using blockchain technology. *2019 TEQIP III Sponsored International Conference on Microwave Integrated Circuits, Photonics and Wireless Networks (IMICPW)*, 174–178. https://doi.org/10.1109/IMICPW.2019.8933270

Mavilia, R., & Pisani, R. (2022). Blockchain for agricultural sector: The case of South Africa. *African Journal of Science, Technology, Innovation and Development*, *14*(3), 845–851. https://doi.org/10.1080/20421338.2021.1908660

Mirabelli, G., & Solina, V. (2020). Blockchain and agricultural supply chains traceability: research trends and future challenges. *Procedia Manufacturing*, *42*, 414–421. https://doi.org/10.1016/J.PROMFG.2020.02.054

Mohanty, S. N., Ramya, K. C., Rani, S. S., Gupta, D., Shankar, K., Lakshmanaprabu, S. K., & Khanna, A. (2020). An efficient lightweight integrated blockchain (ELIB) model for

IoT security and privacy. *Future Generation Computer Systems*, *102*, 1027–1037. https://doi.org/10.1016/J.FUTURE.2019.09.050

Mussenbrock, C. (2022). *Etherisc – white paper 2.0*. https://uploads-ssl.webflow.com/6243075ff83d08a79dc7b307/63bbffeb07508e1d02fc70b4_Etherisc%20Whitepaper%20December%202022.pdf

Nakamoto, S. (2008). *Bitcoin: A peer-to-peer electronic Cash system*. www.bitcoin.org

Niforos, M. (2017). *Beyond fintech: Leveraging blockchain for more sustainable and inclusive supply chains*. Open Knowledge Repository. https://openknowledge.worldbank.org/entities/publication/6dd33df2-68f4-56cb-ad64-12bf41c784b0

Niknejad, N., Ismail, W., Bahari, M., Hendradi, R., & Salleh, A. Z. (2021). Mapping the research trends on blockchain technology in food and agriculture industry: A bibliometric analysis. *Environmental Technology & Innovation*, *21*, 101272. https://doi.org/10.1016/j.eti.2020.101272

Ocaña-Fernández, Y., & Fuster-Guillén, D. (2021). The bibliographical review as a research methodology. *Revista Tempos e Espaços Em Educação*, *14*(33), e15614. https://doi.org/10.20952/REVTEE.V14I33.15614

O'Neill. (2023, October 26). *South Africa: GDP distribution across economic sectors 2022* . Statista. https://www.statista.com/statistics/371233/south-africa-gdp-distribution-across-economic-sectors/

Patelli, N., & Mandrioli, M. (2020). Blockchain technology and traceability in the agrifood industry. *Journal of Food Science*, *85*(11), 3670–3678. https://doi.org/10.1111/1750-3841.15477

Patil, A. S., Tama, B. A., Park, Y., & Rhee, K.-H. (2018). *A framework for blockchain based secure smart greenhouse farming.* In J. Park, V. Loia, G. Yi, & Y. Sung (Eds.), *Advances in computer science and ubiquitous computing. CUTE CSA 2017. Lecture notes in electrical engineering* (Vol. 474, pp. 1162–1167). Springer. https://doi.org/10.1007/978-981-10-7605-3_185

Pavithra, D., & Balakrishnan, R. (2015). IoT based monitoring and control system for home automation. *Global Conference on Communication Technologies, GCCT 2015*, 169–173. https://doi.org/10.1109/GCCT.2015.7342646

Pei, X., Tandon, A., Alldrick, A., Giorgi, L., Huang, W., & Yang, R. (2011). The China melamine milk scandal and its implications for food safety regulation. *Food Policy*, *36*(3), 412–420. https://doi.org/10.1016/j.foodpol.2011.03.008

Perez-Aloe; R, Valverde; J. M., Lara; A, Carrillo; J. M., Roa; I, & Gonzalez; J. (2007). *Application of RFID tags for the overall traceability of products in cheese industries*. *2007 1st Annual RFID Eurasia* (pp. 1-5). IEEE.

Prause, G., & Boevsky, I. (2019). Smart contracts for smart rural supply chains. *Bulgarian Journal of Agricultural*, *25*(3), 454–463.

Pureswaran, V. (2016, February 18). *Blockchain is key to internet of things democracy*. IBM Institute for Business Value. https://www.ibm.com/thought-leadership/institute-business-value/report/device-democracy

Raikwar, M., Gligoroski, D., & Kralevska, K. (2019). SoK of used cryptography in blockchain. *IEEE Access*, *7*, 148550–148575. https://doi.org/10.1109/ACCESS.2019.2946983

Rijanto, A. (2020). Business financing and blockchain technology adoption in agroindustry. *Journal of Science and Technology Policy Management*, *12*(2), 215–235. https://doi.org/10.1108/JSTPM-03-2020-0065/FULL/HTML

Safak, E., Mendi, A. F., & Erol, T. (2019). Hybrid database design combination of blockchain and central database. *International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT)*, 1–5. https://doi.org/10.1109/ISMSIT.2019.8932763

Saunders, M. N. K., Lewis, P., & Thornhill, A. (2019). *Research methods for business students*. Pearson.

Shahid, A., Almogren, A., Javaid, N., Al-Zahrani, F. A., Zuair, M., & Alam, M. (2020). Blockchain-based agri-food supply chain: A complete solution. *IEEE Access*, *8*, 69230–69243. https://doi.org/10.1109/ACCESS.2020.2986257

Swinnen, J. F. M., & Maertens, M. (2007). Globalization, privatization, and vertical coordination in food value chains in developing and transition countries. *Agricultural Economics*, *37*(s1), 89–102. https://doi.org/10.1111/j.1574-0862.2007.00237.x

Szabo, N. (1996). Smart contracts: Building blocks for digital markets. *The Journal of Transhumanist Thought*, *18*(2).

The Malta Digital Innovation Authority Act, (2018). https://legislation.mt/

Tikhomirov, S. (2018). Ethereum: state of knowledge and research perspectives. *Foundations and practice of security. FPS 2017. Lecture notes in computer science* (Vol 10723, pp. 206-221). Springer. https://doi.org/10.1007/978-3-319-75650-9_14

Tripoli, M., & Schmidhuber, J. (2018). *Emerging opportunities for the application of blockchain in the agri-food industry*. (Issue paper), International Centre for Trade and Sustainable Development.

Turvey, C. G. (2001). Weather derivatives for specific event risks in agriculture. *Review of Agricultural Economics*, *23*(2), 333–351. https://doi.org/10.1111/1467-9353.00065

Walliman, N. (2011). *Research methods: The basics*. Sage Publications.

Xiong, H., Dalhaus, T., Wang, P., & Huang, J. (2020). Blockchain technology for agriculture: applications and rationale. *Frontiers in Blockchain*, *3*, 7. https://doi.org/10.3389/FBLOC.2020.00007

Yadav, V. S., & Singh, A. R. (2019). A systematic literature review of blockchain technology in agriculture. *Proceedings of the International Conference on Industrial Engineering and Operations Management*, 973–981.

Yan, H., Yang, J., & Kim, H. (2021). Application of blockchain technology in agricultural products' traceability system. *Asia-Pacific Journal of Convergent Research Interchange*, *7*(12), 55–66.

Yang, X., Li, M., Yu, H., Wang, M., Xu, D., & Sun, C. (2021). A trusted blockchain-based traceability system for fruit and vegetable agricultural products. *IEEE Access*, *9*, 36282–36293. https://doi.org/10.1109/ACCESS.2021.3062845

Yao, Q., & Zhang, H. (2022). Improving agricultural product traceability using blockchain. *Sensors*, *22*(1), 1–23.

Zhao, S., & O'Mahony, D. (2018). BMCprotector: A blockchain and smart contract-based application for music copyright protection. *ACM International Conference Proceeding Series*, 1–5. https://doi.org/10.1145/3301403.3301404