blockchains

Review

Review of Blockchain Applications in Food Supply Chains

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Abstract: Blockchain has found wide acceptance not just in the DeFi and Crypto space, but also in digital supply chains, non-monetary transactions, and governance. Amongst many, the food supply chain is riddled with lots of inefficiencies and untraceable corruption. Hence, many have investigated the integration of blockchain technology into the food system. This paper discusses the major advancement in blockchain technology from the aspect of food security and proposes roadmaps for future applications in businesses. We dive into the different pillars of food security and how blockchains can play a valuable role in the technology infrastructure of food security in a holistic sense. Next, the paper also discusses the organizational, economic, and management aspects of technology adoption. Finally, we end by discussing the nexus between Blockchain and Decentralized Autonomous Organizations (DAO), as well as Digital Twins, respectively.

Keywords: blockchains; food systems; distributed ledger technology; food security

1. Introduction

One of the biggest sectors on the planet is the food sector, which has a complicated global supply chain with several players. The need for digitization in the food supply chain is driven by the rising demands for transparency, traceability, and food safety. Some of the issues in the food supply chain have been recognized, and blockchain technology has been suggested as a potential decentralized and transparent ledger solution. With a focus on its advantages, drawbacks, and potential future improvements, this literature review intends to examine the current level of research on the applications of blockchain technology in the food supply chain. The review will include a summary of the literature that has already been written on the subject, identify gaps and restrictions, and make suggestions for further research.

The Food System consists of all the 'sequential stages directly and indirectly linked to the customers' requests' including (but not limited to) production, transportation, inventory management, and retailing. In its linear form, the process begins with the farmer (producer) and ends with the consumer, with various other players—government, agricultural equipment retailers, logistics companies, food retailers, and inventory managers—in between. These players make decisions that affect various factors of the agricultural produce such as price, quality, shelf life, and nutritional value. Therefore, it is economically critical and socially essential to be informed, rather than ignorant, about the link between the price of an agricultural food product and its quality.

1.1. Challenges of the Food System

In 2021, it was reported by the World Trade Organization (WTO) that 44% of the concerns raised in 2020 at the Sanitary and Phytosanitary Measures (SPS) Committee were related to food safety [1]. Many of these agitations are due to a lack of transparency regarding the nutritional content, nature, processing procedures, and source of imported food. Others include issues such as pricing and policy concerns. For instance, various countries have different acceptable levels of pesticide residue, otherwise known as the maximum residue level (MRL), and other countries have varying tolerances for the nature of

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the food (organic or genetically modified) rooted in various cultural and scientific opinions. This discrepancy between demand and supply, despite the availability of resources, results in massive wastage of food. Therefore, it is economically critical and socially essential to be informed, rather than ignorant, about the link between the price of an agricultural food product and its quality. The new fundamentals challenging food systems and supply chains are:

1. Reducing waste in the intermediate supply chain [2].
2. Increasing collaboration between various stakeholders [3].
3. Managing the contractual procurement of food [4].
4. Managing inventory by smoothing the international customs and finally [5,6].
5. Bringing efficiency to the safety inspection and certification processes of players in the food system [7].

Although there have been many works on technology intervention and organizational strategy implementation, few have studied the scope of blockchain technology to benefit the FSC.

We argue that it is therefore necessary to have a decentralized, ineradicable, and accessible source of information on the authenticity of the global food basket. This achieves multiple goals, including improved organizational efficiency, increased customer awareness, and effective access to quality food produce through efficient adoption of technology, increased trust, and transparency for the end users and, most importantly, matching the price of the produce with its quality. Blockchain is one such technology predicted to help better connect the many players and hand options in the industry bringing efficiency to the many disjointed elements. Broadly speaking, blockchain is a highly secure form of distributed ledger technology (DLT) used to exchange jurisdiction, register transactions [8], track assets [9], and ensure transparency, trust, and security of the digital assets of the food supply chain [10].

Five particular reasons set blockchain applications for the food industry apart from those for traditional financial businesses include:

1. Identifying the participants in each transaction;
2. Understanding the laws governing privacy and secrecy;
3. How transactions are endorsed;
4. How the network is regulated;
5. The assets that are tracked may not always have monetary value.

Either a pre-established policy or a set of tokens can be used to regulate blockchain networks. A collection of rules that are pre-agreed upon by significant stakeholders, such as a group of members, a regulator, or a market, is necessary for policy-based approaches. A token-based policy is based on blockchain governance because the blockchain itself is the means of governing. Depending on the methodology, policy-based governance can be either on-chain or off-chain. Both token-based governance and policy-based governance are examples of well-established real-world systems. While early company blockchains were primarily regulated by policies, an increasing number of businesses' blockchains now include token systems as a way to promote good network behavior.

1.2. Blockchain Technology

Generally, a distributed database that is shared by all of the nodes in a computer network is known as a blockchain. A blockchain is an electronic database that stores data digitally and is mainly used to securely record transactions in cryptocurrency systems such as Bitcoin. The key feature of blockchain technology is that it ensures the fidelity and security of data records, without the need for a trusted third party, which instills confidence in the system. Unlike traditional data organization, the data in a blockchain are organized in blocks that have specific storage capabilities and are linked together in a chain. Each block contains a set of data and is sealed when filled, and the subsequent information is stored in a new block, which is added to the chain once it is full. According to Investopedia [11], the net worth of assets in the bitcoin blockchains together is worth trillions of dollars. The food supply chain, on the other hand, is a complex system with many nuances and intricate processes. On the whole, the food system is one of the most technologically redundant systems in the world. The major difficulties in an agri-food supply chain include a lack of mechanization, inadequate management, inaccurate information, and ineffective supply chains. There is a wide body of research that suggests blockchains ought to be integrated with the food supply chains to make them more transparent, traceable, and trustworthy [12,13]. In this study, we conduct a background investigation and literature review to understand the effects of blockchain adoption in the food supply chain. This includes technology effects, management and economic effects, and, most importantly, perceived social and behavioral effects. We also investigate prospects for future research in this regard.

1.2.1. Features of Blockchain Technology

Blockchain technology has four highlight features that set it apart from other ledger systems (centralized). These are provenance, finality, immutability, and algorithmic consensus. Provenance refers to a full record of every transaction involving the assets that were made and stored on the blockchain. Finality, on the other hand, means that once a transaction is committed to the blockchain, it is considered "final" and can no longer be "rolled back" or reversed. Thirdly, a transaction cannot be altered, deleted, or have transactions added before or after it has been recorded on the blockchain. This property is referred to as the immutability of blockchains. This feature allows the user to audit records without fear of human errors. Lastly, consensus refers to the procedure of selecting new transactions, distributing them to network users, and creating a common agreement on the history of transactions.

Smart contracts are computer programs that run when certain circumstances are satisfied and are kept in a blockchain database [14]. Frequently, they are employed to automate the execution of an agreement to ensure that all parties can immediately and confidently conclude without any intermediaries or additional delays. Moreover, they can automate a sequence of actions so that when specific conditions are met, the subsequent actions are performed. Smart contracts on a blockchain operate by utilizing simple conditional statements, such as "if/when . . . else/then", encoded into the code. When certain predetermined conditions are verified by a network of computers, specific actions are executed such as paying out money, registering a car, sending notifications, or issuing a ticket. Once the transaction is completed, the blockchain is updated, and the outcome can only be viewed by authorized parties, ensuring that the transaction cannot be altered.

The capability to transact data in a decentralized manner and automate tasks based on pre-coded conditions on a distributed database gives rise to applications with a unique property called decentralized governance. That means, such web applications are no longer coupled to an individual owner or company; rather, they are run and governed by the joint consensus of everyone who has a stake in the application. Such applications are called decentralized apps or DApps. A decentralized application is referred to as trustless or player-to-player and differs from a client–server architecture in that there is no single server or controlling entity. It is this property of DApps that makes them an ideal candidate to bring trust and coordinate activities between trustless parties in a secure and transparent manner without compromising data integrity.

1.2.2. General Data Structure of BCT

Every database stores information in a specific structure. These structures can take the form of tabular models, ER models, dimensional models, hierarchical models, etc. In the case of blockchain, 'blocks' are the fundamental unit of storing information. The structure of a blockchain, along with its block data structure, is depicted in Figure 1. Headers, transactions, states, and cache are the several types of data that compose a blockchain. Each one has distinctive qualities if you consider them to be a group of cumulative sets.

1. Header—The structure of the smallest unit that makes up a "chain" is known as the header. It includes fundamental details such as the timestamp and the previous block's hash. The Merkle root of transactions and states is also included. This is so that all of the data in the Merkle tree can be verified simply by checking the headers.
2. Header + Transaction—The combination of all the headers and all the transactions is what we refer to as the "blockchain" itself. The other nodes validate the "blocks" published by the nodes that mine or propose a block. It is the smallest piece of data that can represent the entire network since it is feasible to determine the status of the entire blockchain from just a chain of headers and transactions, which is the fundamental unit utilized in actual chains.
3. Header + Transaction + State—The maximum range that the header can verify is when the state is added to the prior data set. It is also the biggest collection where the protocol expressly guarantees that every node has the exact same value. The complete node maintains this data collection. Additionally, it is the bare minimum of data required to validate an entire block. Therefore, in order to verify and vote on the newly proposed block, we require the data set that has been described thus far.
4. . . . + Cache—From this point on, each node is free to have any value, irrespective of protocol. There is no need for and cannot be a verification of these data because it depends on the implementation.

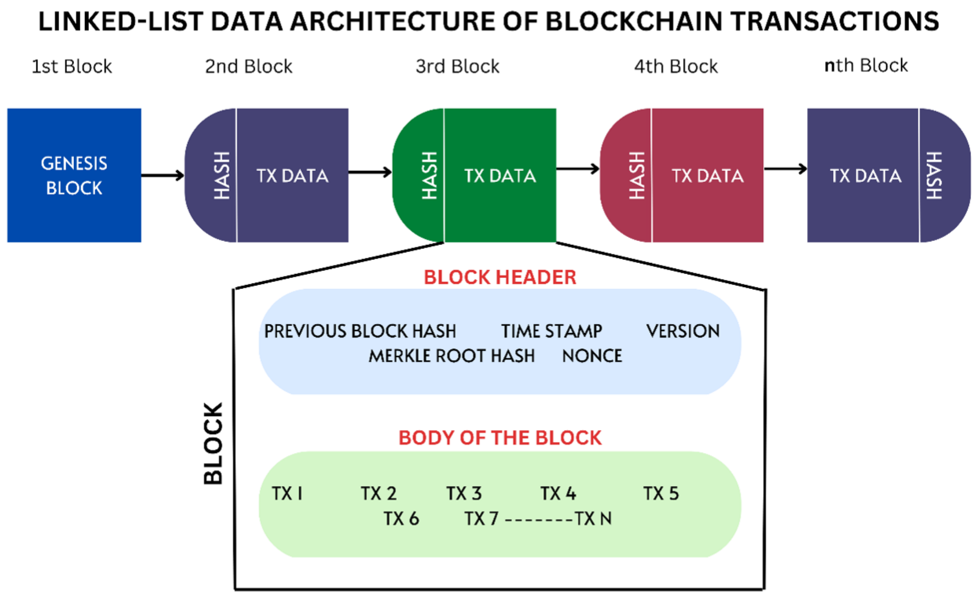

Figure 1. General Data Architecture Used in BCT.

A cryptographic technique for obscuring data is hashing. In the context of blockchain, a hash is any number that reflects data recorded in chain blocks. The hash will change if data in blocks are altered, indicating even the tiniest indication of data tampering. A hash function is a mathematical operation that transforms an input string of any length into an output string of a specific length. An infinite number of bits are input into a hashing algorithm, which then uses those bits to conduct calculations to produce a set number of bits. As a summary of all transactions in a block, a Merkle Tree is a mathematical data structure made up of hashes of different blocks of data. The data are hashed for encryption, ease of verification, ease of indexing, and retrieving information. Additionally, it makes large-scale content verification secure and effective. Additionally, it helps with the content and consistency checks of the data. Bitcoin and Ethereum both employ Merkle Trees. Hash Tree is also known as Merkle. Lastly, hashing acts as a digital fingerprint for the data.

2. Materials and Methodology

The topic of food systems and blockchains is quite broad and abstract in nature, with lots of elements and facets that need to be taken into account. Therefore, we adopted a systematic literature review with specific concern for the effects and complexities of blockchain adoption into the food system. As the objective of this study was to review the present status of the literature in the area of food systems and blockchain technology, we conducted a systematic literature review combined with content analysis as proposed by Jauch et al. (1980) [15] and Mayring (2004) [16].

The applied methodology used a four-step iterative process that consisted of: (i) material collection, (ii) descriptive analysis, (iii) category selection, and (iv) material evaluation. To have holistic coverage of all the possible materials, we used Scopus, IEEE, and Google Scholar as our sources of articles. The basic search criteria included that the papers were published during the years 2017–Present. The following keywords that were searched for in titles or keywords included (*Food Systems* OR *Food Supply Chain*) AND *Blockchain Technology*. The search results were subjected to various screening and filtering conditions in order to arrive at the required set of literature. Finally, 89 papers were collected, classified, and analyzed for this literature review. While reviewing, their distinguishable characteristics were recorded in a spreadsheet to be analyzed holistically. This study aims to analyze 89 scientific publications published between 2017 and 2022. The screening process is mentioned in Figure 2 above. The existence of partial literature reviews in this area must be acknowledged here to clarify the need for this study. Table 1 mentions the renowned publications in this field with their respective scope of study. Paper Scope Methodology.

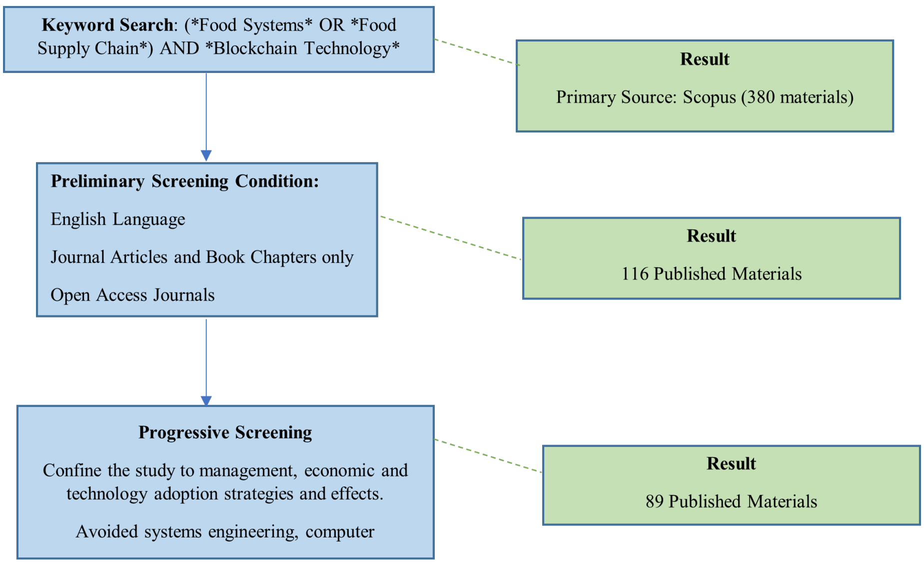

Figure 2. Review Methodology.

Table 1. Previous Literature Reviews On Blockchain Technology and Their Scope in Food Systems.

Paper	Scope	Methodology
[17]	Technical review of blockchains	Surveys and case studies
[18]	Application-based review of blockchains in various spheres of activity	Comprehensive review
[19]	Application-based review of blockchains in various spheres of activity	Systematic literature review
[20]	Blockchain and IoT in precision agriculture	General review of scope and technicalities
[21]	Trend analysis and future scope of blockchains.	Bibliometric study
Our study	Pillars of food security and the effects of BCT adoption	Systematic literature review and content analysis

The rest of the paper is divided as follows. The following section details the various aspects of the food systems and how blockchain technology fits into these aspects. This is then followed by possibilities for future work and the conclusion of our work.

3. Discussions

With features such as immutable provenance, blockchains enable trade parties to facilitate port checking and clearance processes faster and more efficiently. Through the use of IPFS, blockchains can be used to access storage systems to verify origin certificates and lab test certificates in a secure manner—thus promoting on-spot food safety assessments and new food labeling techniques. The most important aspect of blockchains is that their integration with existing infrastructure (IoT, QR scanner, Big Data algorithms) has been demonstrated in the literature. These capabilities render them the ability to detect and prevent fraud from happening in the food value chains.

Table 2 gives a list of blockchain applications in the food industry. Blockchains offer the ability to conduct financial and certificate audits of the food value chain. Blockchains have been studied in the issue of carbon credit tracking, hence helping businesses to track their emissions and make amends to their corporate social responsibility strategy. Blockchains are a decentralized ledger that keeps a record of all the transactions and provenances in a particular business. This helps stakeholders to avoid compliance violations and verify safety code adherence.

Table 2. Previous Blockchain Applications in Food Systems.

Food Reference	Goal	Advantage	Result
Beef [22]	Quality assurance for consumer's choice	Informed policy making	Traceability
Halal Food [23]	Trusted information throughout the FSC	Guarantee of food safety and data protection	Reliability
Tea [24]	Steer stakeholder attitudes to adopt sustainable production	Healthy competition	Transparency
Fish [25]	Tracing Shellfish quality	Improve food safety management	Quality
Olive Oil [26]	Tracing food prices while ensuring bi-direction communication between the company and the consumer	Easy integration with existing systems and technologies	Fraud prevention
Rice [27]	Tracing source and giving credit to farmers	Greater sense of appreciation for farmers	Provenance
Agri-food [28]	Allow quality to be certified	Retailers can justify the sale of "Premium Vegetables"	Better food pricing
Dairy [29]	Create a supply chain void of data silos	Giving privacy to individual stakeholders while also ensuring disclosure of necessary data	Management
Soybean [30]	Security through transparency and brand imaging	Consumer loyalty	Trust
Sugar [31]	Increase competitiveness	SC resilience	Traceability
Eggs [32]	Ensuring food safety	Improve food safety	Fraud prevention

Blockchain-based food traceability platforms, protocols, and services are used by some of the world's leading food companies, including Walmart, Nestlé, and Dole. These platforms allow companies to track the movement of food products from farm to table, ensuring that consumers have access to safe and authentic food. We will look at the evolution of BCT with respect to its commercial applications with the help of specific network examples.

3.1. Evolution of Blockchain Application in Food Supply Chains

Let us now discuss the applications of blockchain technology within the food supply chain over the past years. In Figure 3, we discuss how blockchain applications and various protocols have helped in transitioning from a mundane, paper-based, time-consuming, process-centric system to an automated, highly transparent, hassle-free people-centric system. This transition did not come about in a snap; rather, it came about through the focused efforts of the industry and research experts. We will discuss some of these networks and highlight their features, advantages, and drawbacks.

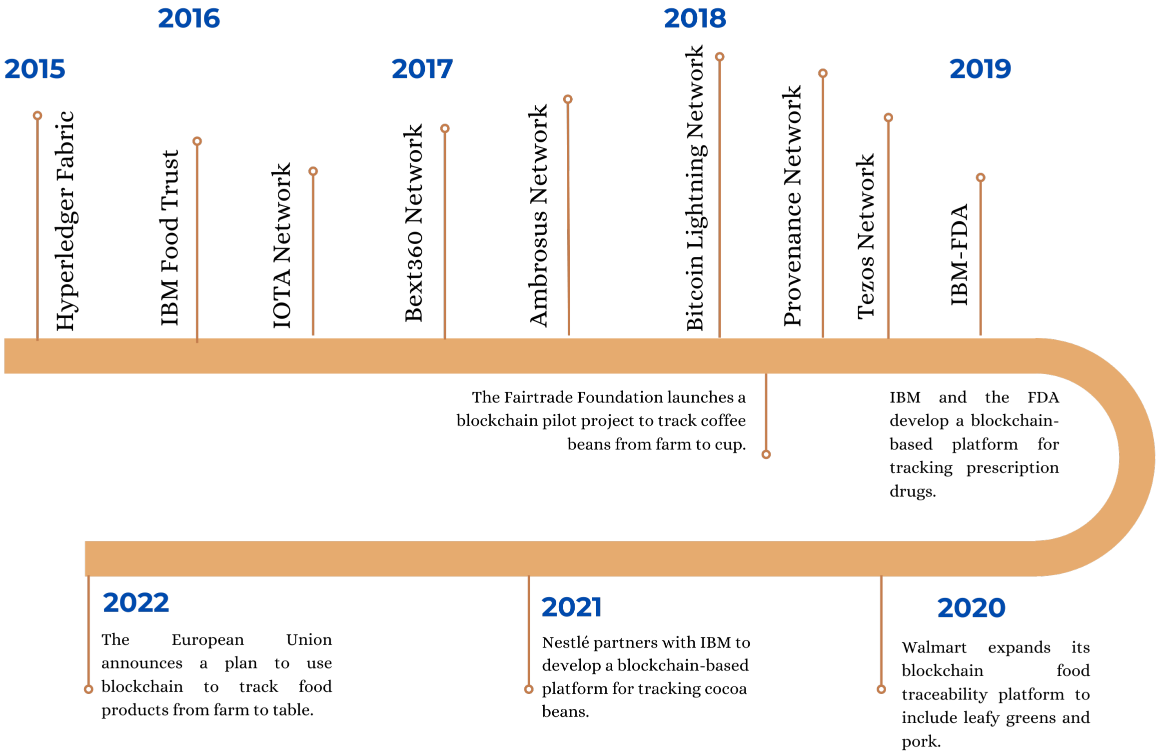

Figure 3. Evolution of Blockchain Technology Application in the Food Supply Chains.

Although there exists a wide variety of blockchain networks and protocols, very few have been targeted for supply chains and their business-use cases. Bitcoin and Ethereum have made many strides in blockchain technology. The earliest applications of BCT in the food sector were primarily flagged by Hyperledger fabric in 2015. Hyperledger Fabric is an open-source blockchain framework developed by the Linux Foundation. Hyperledger Fabric can be used to ensure that food businesses comply with regulations. For example, it can be used to track the use of pesticides and other chemicals in food production. In 2016, IBM Food Trust was launched. It is a permissioned blockchain, which means that only authorized participants can join the network. This makes it ideal for use in sensitive industries, such as food safety. IBM Food Trust participants include Walmart, Nestlé, Dole, Tyson Foods, Unilever, Kroger, McCormick, McLane Company, Driscoll's, Golden State Foods, and Seven Seas Tuna.

IOTA (2016) [33] is a distributed ledger technology (DLT) that uses a unique consensus mechanism called the Tangle. The Tangle is a directed acyclic graph (DAG) that allows for transactions to be confirmed without the need for miners or fees. This makes IOTA ideal for use in applications where high throughput and low cost are essential, such as the food supply chain. Provenance, Connecting Food, FreshFarm, InFoodChain, and Farm2Kitchen are some of the companies that use IOTA in their food supply chains. Bext350 uses a permission blockchain protocol called Stellar [34] that can aid in higher transactions per second. The Ambrosus protocol (2017) [35] works by creating a shared ledger of food provenance data using IoT sensor (hardware-in-place technique) data sharing. These data include information such as the origin of the food, the date and time of production, the location of each step in the supply chain, and the temperature and humidity conditions at each step. This information is stored on the blockchain in an immutable ledger, which means that it cannot be tampered with. Bitcoin Lightning Network [36] is a second-layer payment network that runs on top of the Bitcoin blockchain. It allows for fast and cheap payments between users, without having to wait for confirmations on the blockchain. Farm2Kitchen:

Farm2Kitchen is a food traceability platform that uses the Lightning Network to track the movement of food products from farm to table.

There are other milestones witnessed in the evolution of BCT to help smooth adoption within supply chains. The EU is a leading force in the global adoption of blockchain technology. The laws and regulations that the EU has adopted, as well as the funding that it is providing for research and development, are helping to make these technologies more widely available and to create a more favorable regulatory environment for their use. Some of the key EU laws and bills that talk about the adoption of blockchain technology and smart contracts are DSA, MiCA, and BRT. The Digital Services Act (DSA) is a proposed regulation that aims to regulate online services, such as social media platforms and search engines. The DSA includes provisions that promote the use of blockchain technology and smart contracts. For example, the DSA requires online platforms to provide users with access to their data in a machine-readable format, which could be used to create smart contracts.

Markets in Crypto-Assets Regulation (MiCA) is a proposed regulation that aims to regulate crypto-assets, such as Bitcoin and Ethereum. The MiCA includes provisions that promote the use of blockchain technology and smart contracts. Finally, the Blockchain Technology Regulation (BRT) is a proposed regulation that aims to create a legal framework for the use of blockchain technology in the EU. The BRT includes provisions that address a number of issues related to blockchain technology, such as data protection, liability, and consumer protection.

3.2. Blockchains and Food Security

Based on the proceedings of the World Summit on Food Security (2009) [37], Galanakis (2020) [38] defines Food security as a situation

> "when all people at all times have physical, social and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life ".

Four pillars of vital importance have emerged from this definition of food security. They are availability, accessibility, stability, and utilization. There are many issues troubling the food system. These include climate change, population growth, food fraud, and urbanization. These problems not only threaten urban food systems but also global supply chains. Blockchain technology has the ability to benefit lower-income households and, at the same time, to help farmers; to have a substantial impact on a community's food system traceability, waste reduction, and responsible consumption; to reward stakeholders and players for their sustainable actions; and to vote for food system governance. The four main pillars of food security—availability, access, utilization, and stability—are seen by experts as essential to ensuring its sustainability [39–41]. Nutrition and food security are related, although malnutrition and food insecurity are not. Malnourishment may not always result from a lack of food because families may have access to nutritious diets but choose to eat poorly or because of hereditary diseases. This calls for the necessity of traceability solutions so that consumers can be made aware of the consequences of their choices. The lack of means to produce or access food in general, or nutritious food in particular, is linked to malnutrition in many regions of the world since healthier diets are more expensive than diets high in calories but low in nutrition. In such cases, blockchain-based solutions can intervene to engage in crowdfunding projects that are later sanctioned as initial coin offerings (ICOs), and the public can own a small share of such sustainability and poverty eradication projects. Furthermore, the effects and solutions offered in the food system can be studied based on the verticals of food security mentioned earlier.

Availability: Food availability refers to the tangible existence of food in a satisfactory quantity, proportionate quality, and the proper means to make it available through domestic production, food import, food aid, or a combination thereof. It is clear that food availability is a concept that concerns the supply side of the food system. Lutz et al., (2002) [42] pinpointed that food insecurity is generally brought on by a growth in population, poverty, gender inequality, education, and other important issues that negatively affect food production.

At the community level, Kurtsal and Viaggi (2020) [43] infer that SFSCs can overcome these sustainability challenges by directly interacting with the producers and distributors within the locality of Izmir, Turkey. They, along with Harrison et al. (2019) [44], who studied the SFSCs in Australia, conclude that national policies should target the promotion of local food produce and direct producer-to-consumer sales channels. Another major advantage of the localized food system is the proximity of food producers and consumers of food, which reduces food miles. Accorsi et al. (2018) [45] highlight the need for vendors to establish horizontal communications with logistics and vertical integration using an integer linear programming model. In closing, it is noted that engaging the community through campaigns [46], technological innovations [47], and effective governance [48] to promote product, process, or market innovations will help all players of the FSC to achieve their objectives [49].

Accessibility: Unlike food availability, food accessibility refers to the demand side of the food system. It refers to the physical infrastructures that are required in order for households and individuals to consume food. This is satisfied through physical facilities such as roads, water transports, physical stores, and economical facilities, such as income and employability, ensuring that buyers have the necessary buying power to consume food at a nominal, assured, and nonfluctuating price. Lee et al. (2013) [50] studied how cost affects people's access to food. Inadequate market infrastructure drives up the cost of transporting produced food into domestic or international markets and drives up the cost of inputs such as water and fertilizers. Individual food security, as opposed to household food security, is influenced by a variety of apparent and invisible intra-household factors.

Stability: Stability refers to the ability of the other three pillars to achieve their goals continuously and consistently. Stability is both a short-term and a long-term concern that is affected by internal factors, such as food price, organizational collaboration, food inspection, and population growth, and external factors, such as geo-political tensions, climate change, natural disasters, and others [51]. Current global supply chains often suffer from outdated, slow, and expensive processes that can cause difficulties for participants, particularly smaller producers or distributors. Even in the most efficient supply chains, the multiple stakeholders and intricate commercial relationships require complicated governance structures that are challenging to manage with current practices. The stability of a food system is ensured by good governance and policy intervention.

Governments spearhead the enactment of policies. Laureati et al. (2015) [52] demonstrate how governments can promote sustainable practices in the fish supply chain in Rome, by implementing public procurement for school canteens. They identify that the main enabler of government policy is a behavioral shift in food consumption towards nutrition-rich meals. Smith J et al. (2016) [53] also explore the notion of sustainable public procurement at the organizational and national level to meet the growing demands of food in the light of social, economic, and environmental constraints. On the local level, Moragues-Faus et al. [54] conduct a Delphi survey to study all the present and future drivers of the food system and discuss the threats to the food system. From the survey, the authors bring out five major contributors to the lack of cooperation in food systems and conclude that consumption is the main driver for policy implantation. It can also be noted that governments must issue policies that make consumer–producer interactions (CPI) more transparent, devoid of intermediaries, and protected from fraudulent practices. Opitz et al. (2019) [55] explore the most important properties that govern CPI among six identified domains. As pointed out by K. Smith and Lawrence (2018) [56], in the event of a massive disaster, most of the governmental policies trickle down to the community level but not at the individual or organizational level. Using the case of the Queensland flood of 2011, the authors advocate that an 'adaptive' governance approach must be adopted in such cases to ensure quality cooperation and collaboration between the players in the food system.

Utilization: Once the necessary conditions for availability and accessibility are satisfied, food security also demands that the consumers are able to consume healthy and nutritious food. Utilization refers to the manner in which consumers intake healthy nutritious food. Utilization is deeply rooted in food behavior, consumption habits, awareness of nutrients, food preparation, and hygiene conditions. Among the various goals of collaboration in the FS, perhaps the importance of food security weighs the most. Maggio et al. (2016) [57] and Ocampo et al. (2018) [58] found that socially responsible businesses were one of the three significant drivers of sustainable practices. As highlighted by Paloviita et al. (2016) [59], food security is an enabler of collaboration amongst FS players and can only be achieved using a system approach. Bunting and Little (2015) [60] and Allan et al. (2015) [61] conclude that urbanization is one of the biggest hindrances to food security and, therefore, one of the strongest drivers of collaboration between the influencers and players of the food system. With the growth of urban livelihoods, food security has become a major concern due to visible and invisible factors in transferring the current scientific assessments to the urban framework (Haysom and Tawodzera, 2018) [62]. As observed by Ozor et al. (2016) [63], tighter interdependencies of the rural–urban food system are a major threat to the availability of food. Mantino and Forcina (2018) [64] explored the role of the localized agri-food systems (LAFS) in densely populated, industrialized communities and proposed methods to maximize the profit level per hectare by suggesting policy interventions within stakeholder connections. Forssell and Lankoski (2018) [65] and Cerrada-Serra et al. (2018) [66] proposed the concept of alternate food networks (AFNs) as a solution towards sustainability in the food system and examined the actors of transition thereof. Along the same lines of thought, Huang and Drescher (2015) [67] and Gulyas and Edmondson (2021) [68] proposed urban agriculture (UA) as a solution that would contribute to food system resilience by tackling sudden shocks to the market. However, as pointed out by Di Fiore et al. (2021) [69], there is still a gap in the literature regarding a framework for UA and how it will interact with the export/import policies of a country. Many have argued that this, in turn, will also help to design a circular economy model. Formentini et al. (2021) [70] investigate the concept of waste hierarchies and frameworks to reduce FLW in the FSC that adopts circular economy principles. Others, such as G. Singh et al. (2022) [71], inferred that the main causes of waste in the processing sector of emerging nations such as India are the high costs of cold chain facilities (IFPS). Turan and Ozturkoglu (2022) [72] studied a conceptual framework that helps to analyze the performance of perishable foods in the cold supply chain. Gokarn and Kuthambalayan (2017) [73] do an excellent job of identifying 33 challenges associated with the reduction in food waste in the AFSC. Further, they conducted ISM, EFA, and MIMAC analyses on these inhibitors and found that perishability, quality variation, and seasonality of food scored the highest in a factor analysis while inefficient procurement, transportation, and distribution scored the least. Table 3 lists all the intersections between the food security pillars, the visions of food security, and the existing solutions available in the blockchain literature.

Table 3. Mapping the Benefits of Blockchain Technology to the Various Pillars of Food Security.

Aspect of Food Security	Problem	Solution	Result and Reference
		Availability	
Social barrier	Ensuring there is no corruption	More reliable and secure transactions and ledger keeping	Healthy supply chain practices [74–76]
	Establishing direct B2B and B2C channels	Reduced transaction costs and increased transaction capacity	Establish various sales models [77,78]
	Ensuring farmers are paid regardless of gender	Promote fair practices using blockchain	Farmer recognition and increased self-esteem [79]
Food loss	Encouraging stakeholders to reduce food loss/waiting in supply chain inefficiencies	Public, immutable, ordered ledger with appropriate information	Reduced food losses [75,80,81]
	Encouraging responsible consumption with a tokenized reward system	Blockchain-based token rewards for responsible buying	Increased public participation towards sustainable alternatives [82,83]
		Accessibility	
Food infrastructure	Efficient food trading and distribution system	Decentralized food procurement and transaction system	Zero dependence on one body for procurement [84–86]
	Smoothing customs/air/rail/port/checking processes	Blockchain-based smart contracts for verifying documentation	Reduced waiting/inspection time [77,87]
		Stability	
Food price	Bringing transparency: price that reflects the quality	Traceable supply chain	Consumer trust and reduced price volatility [29]
Access to market data	Permissioned access to data without compromising security and privacy	Tokenized access based on KYC credentials issued in a blockchain system	Earn monetary benefits for sharing data [88–90]
Funding for food safety net programs	Democratized platform for funding socio-economically viable, sustainable projects	Blockchain-based crowdfunding and ICO	Reduces financial burden on governmental institutions [91,92]
		Utilization	
Nutrition labeling	Consumers need more information (country of origin, date of manufacturing, method of cultivation, etc.)	Blockchain-based QR Code stickers on food products	Integration with existing technologies and increased loyalty [93,94]
Nutrition monitoring	Both consumers and public institution need mechanisms to monitor freshness of food	Blockchain of things (IoT-based solution secured by blockchain)	Increased brand loyalty and public health [14,95,96]
Natural resource	Land deforestation	Verifiable afforestation schemes and sustainable business models	Consumers can vote with their money [82,97]
	Ground water depletion		
	Marine bio-diversity depletion	Strengthening the food–water–energy nexus.	Opportunities to monitor, track carbon emissions, energy consumption, transactions, etc. [98,99]
	Energy depletion		

3.3. Social, Cultural, and Economic Aspects of Blockchain Adoption in Food System

The digitization of a supply chain or an organization is also accompanied by the socio-technical processes of applying innovation to a system. Introducing blockchain-based interventions for on-chain and off-chain (broader perspective of the food system) activities will result in dealing with all sorts of data for effective management, predictions, and procedures. There are still a lot of questions regarding how stakeholders will actually use blockchains in the food supply chain, despite several promises and case studies about their development. It is therefore important to understand the behavioral and institutional responses to blockchain technology from different angles. These angles include legal, geo-political, human-computer interaction, innovation management, design thinking, and policy studies. In Table 4, we elaborate on these concepts and provide some starting references regarding this aspect on a thematic basis. Kouhizadeh et al. (2021) [100] studied the various factors and drivers for blockchain technology using the DEMATEL approach and found out that there are various technological and sociocultural constraints that limit blockchain adoption. Together with these friction points, there are also collaboration points that compel stakeholders to use blockchains. These include greater access to market data, better self-esteem, and job automation. As pointed out by Faisal and Talib (2016) [101], traceability of products, processes, sanctions, and other critical information is vital to food supply chain governance. A major driver identified in our study was the need for e-traceability. Sinha et al. (2019) [102] found that one of the biggest enablers of e-traceability is appropriate technology and competitive advantage between firms. Blockchain as a proponent of transparency was proposed by Saurabh, Samant, and Dey (2021) [99] by providing a framework and architecture for blockchain adoption. H. Mishra and Maheshwari (2021) [103] investigated the application of blockchain in the public distribution system of India. The authors prove that such technology framework adoption can avoid grain leakages and diversion from the warehouses. George Reno Varghese et al. (2019) [89] investigated the novel concept of integrating blockchain technology with restaurants. It must be remembered that blockchain is still at its infancy and comes with its fair share of disadvantages. Kumar et al. (2020) [104] explains the ground reality of blockchain. It is an expensive, high-overhead storage medium. It is therefore viable only when organizations want to secure highly sensitive information and its high cost can only be counterbalanced by the set of benefits it can give to the entire food system players. Other approaches used towards the goal of traceability were Durresi (2016) and Jakkhupan et al. (2015) [105], who highlighted the role of ICT and RFID technology for food traceability, respectively.

Table 4. Social, Cultural, and Economic Aspects of Blockchain Adoption in Food Systems.

Theme	Disciplines Involved	Result	Reference
Adoption of Digital Technologies in Food System	Technology adoption theory, adoption diffusion theory	Greater access to market forces and control	[106–108]
	Behavioral psychology, human–computer systems	Better production/consumption awareness	[109–111]
Effects of Digitization on Stakeholder Identity, Farmer Skills	Gender studies, farming studies, geo-political studies	Data-driven management may replace farming's "hands-on" and experience-driven management style as a result of digitization	[112–114]
	Identity theory, assemblage theory, institution theory	Major cultural impact on stakeholder identity	[115–117]
Power, Ethics in Digitalizing Agricultural Production Systems and Ownership, Privacy	Legal Frameworks, technology ethics, governance	Computer codes that produce understandable smart contracts	[118–121]
	Cost benefit modelling, optimization	Smart contracts built-in with optimal level of accepted governance logic	[122–125]
Knowledge Management and Innovation in Agri-Food Industry	Economics, management theory, value chain theory	Value and impact of food is extracted in the value chain—both downstream and upstream	[126–128]
	Risk analysis, innovation systems	Evaluate, assess, and analyze wider acceptance of technology	[129–131]

Since blockchain technology is aimed at smart contract-based automation, it is possible that those who are not digitally literate may develop an aversion towards its adoption. Some argue that this will cause losses of jobs and differences of interests. Others argue that digital technologies may merge with existing practices and create a combination of 'digital' and 'analog' skills. With regard to the ownership and legality of blockchains, numerous questions arise and are currently under investigation. These include, understanding and including temporal aspects into smart contracts, designing human–machine readable smart contracts that are both legally and digitally viable, privacy and data ownership, and ethics.

3.4. Legal and Regulatory Compliance

As mentioned by Wang et al (2019) [132], blockchain security risks include transaction-ordering dependence (TOD), where the miner-dependent execution order creates vulnerabilities; timestamp dependence, allowing attackers to manipulate contract-triggering timestamps; and mishandled exceptions, where unchecked returns from contract calls pose threats. Re-entrancy vulnerability permits attackers to exploit contract re-entry, leading to loops such as the DAO attack. Moreover, Ethereum's limited callstack depth of 1024 frames can be overflowed by adversaries to disrupt victim functions if not properly handled.

As mentioned by [133], a smart contract does not create obligations in the legal sense. The author highlights that according to the classical definition of the term 'obligation', it is hard to argue that blockchains provide the key elements of an obligation, namely the future orientation of the contract and the ability to 'will' between the service provider and the service receiver.

1. Food Safety Regulations: The food industry is heavily regulated to ensure consumer safety. Implementing blockchain should align with existing regulations such as the Food Safety Modernization Act (FSMA) in the United States or the General Food Law in the European Union. Blockchain can aid in meeting compliance by providing an immutable record of food provenance and quality.
2. Data Privacy and Protection: Blockchain records are immutable, but they can still contain personal or sensitive data. Compliance with data protection regulations such as the General Data Protection Regulation (GDPR) requires careful handling of personal information stored on the blockchain. Ensuring that only necessary and compliant data are stored is crucial.
3. Product Labeling and Claims: Blockchain can help verify product claims such as organic, non-GMO, or fair trade. However, misrepresentation can still occur, and blockchain implementation should not violate labeling regulations or mislead consumers.
4. Customs and Trade Regulations: For international food supply chains, blockchain can streamline customs and trade processes. However, adherence to import/export regulations and tariffs remains essential.

As the potential for enforcement and liabilities remains, concerns surrounding contract establishment are similar in both conventional and smart contract realms. The key distinction lies in the accuracy attainable when specifying and incorporating terms. Any uncertainties must be addressed by a functional program, leaving no space for ignorance or disregard.

3.5. Data Ownership and Security Concerns

Data ownership and security concerns in relation to blockchain revolve around the challenges of identifying rightful data owners, maintaining control over shared data, and ensuring protection against unauthorized access. While blockchain's distributed nature offers enhanced data integrity, its public and immutable nature can lead to privacy issues. Balancing transparency with confidentiality and addressing potential vulnerabilities in smart contracts and access controls are essential for addressing these concerns.

1. Ownership of Data: Blockchain's decentralized nature raises questions about who owns the data stored on the chain. Participants might share ownership, but determining access rights and responsibilities should be defined through smart contracts and legal agreements.
2. Liability for Data Accuracy: Blockchain's immutability can be a double-edged sword. While it prevents tampering, erroneous data entry can become a permanent record.

Establishing protocols for data verification and correction mechanisms is crucial to preventing legal disputes.

3. Smart Contract Ambiguity: Smart contracts on the blockchain automatically execute actions when predefined conditions are met. Ambiguities or unforeseen situations could lead to contract disputes. Legal experts should review and ensure smart contract language is precise and comprehensive.
4. Cross-Jurisdictional Legal Challenges: The food supply chain often crosses international borders, introducing diverse legal frameworks. Blockchain implementation should consider how it complies with varying laws related to contracts, data protection, and more.
5. Product Recalls and Liability: Blockchain's traceability capabilities can expedite recalls, but they also raise questions about shared liability in case of a recall. Clear agreements regarding responsibility and processes are crucial to managing such scenarios.
6. Smart Contract Failures: If a smart contract malfunctions, resulting in financial loss or other damages, liability becomes a concern. The legal status of smart contracts and their enforceability vary by jurisdiction and should be addressed in contracts.

One of the key challenges and risks in blockchain security pertains to the absence of established standards and regulations. In a study by Juels et al. [134], the notion of criminal smart contracts (CSCs) was introduced, highlighting several typical instances of CSCs, such as the exposure of confidential data, theft of cryptographic keys, and engagement in real-world criminal activities such as murder, arson, and terrorism. The lack of effective regulatory mechanisms makes it challenging to monitor and address these malicious activities within smart contracts. Given the significant security vulnerabilities associated with blockchain and smart contracts, regulatory bodies such as the U.S. Securities and Exchange Commission have started acknowledging the regulatory and operational hurdles that stem from these emerging technologies [135].

4. Future Work

The future applications of BCTs and DLTs within the food value chain comprise creating identity and access management (IAM) systems as well as creating and sharing tokens throughout the supply chains.

4.1. Supply Chain Identity Management

In a completely or partially decentralized business, it is necessary for entities to be able to identify, manage, and communicate effectively with the right players without falling prey to any fraud or identity theft. Moreover, enterprises should be able to serve their clients globally and locally while maintaining a universally accepted Know Your Customer (KYC) identity. The proposed identity management tool will help anyone maintain a legitimate identity in the blockchain network while also choosing to reveal 'what' to 'whom'. In fact, one of the greatest advantages of Web3.0 is the eradication of data silos and the espousal of full ownership of an individual's identity. In short, blockchains can provide a traceable identity token to any legitimate entity on the network.

4.2. Utility Tokens

Utility tokens are backed by both tangible and intangible assets. These include tangible tokens: factories, trucks, machinery, land, electricity, and ownership documents' intangible tokens: identity, copyrights, brands, patents, formulas, lab results, and health conditions. We have listed a few examples below to understand how utility tokens will be used in food supply chains.

4.2.1. Ownership Tokens—Traceability without Compromising Security or Privacy

The biggest problem of the supply chain is the lack of trust between its players and the increased complexity with regards to quality checking, financial auditing, asset management, and security. Supply chain visibility is defined as 'being informed of supply chain interruptions and exceptions, or "capturing and analyzing supply chain data that guides decision-making, reduces risk, and enhances procedures." (Caridi et al. 2014) [136]. The benefit of using tokens is that there is no mathematical connection between the tokens and the actual data they represent. As reversal cannot yield the true data values, a breach makes the information priceless.

4.2.2. Asset Backed Tokens—Recognition and Royalties

Farming is the backbone of any food industry. Despite its importance, farmer suicides, low return for produce, increased farming debt, and corporate monopoly are problems that are still puzzling the food supply chain. Blockchain and Web3 can combine the power of tokenization and smart contracts to solve these issues. The rights to an asset can be stored in a blockchain, and these rights can be transferred for 'value'. Farmers, for example, can claim recognition and royalty should their produce be of higher quality and consequently higher demand in the international market. Smart contracts can be designed in such a way that farmers are made aware of the market retail price without necessarily revealing the profit cut of each participant or compromising corporate privacy.

4.2.3. Green Tokens—Carbon-Credit-Based Life Cycle Assessment

The systematic examination of the potential environmental effects of goods or services over the course of their entire life cycle is known as a life cycle assessment (LCA). By monitoring every stage of a food product using IoT and/or barcode technology along with the traceability and provenance offered by blockchains, it is possible to handle the carbon footprint and further aid in carbon offsetting and trading. Owing to its importance and extensive use, LCA has discovered a proposal for the ISO standards (Guinée and Heijungs, 2017) [137]. The ISO 14040-14043 standard defines the principles, frameworks, and guidelines for conducting life cycle assessments (Rebitzer et al., 2004) [138]. Recent empirical studies [139,140] (Eccles et al., 2014; Flammer, 2013) discovered that investors reward companies that practice sustainability well and penalize those that ignore their social duty. Big companies also have more clout, which puts them in a stronger position to exert pressure on and provide incentives to supply chain partners so that they will work with them to use blockchain technology. Blockchain-based LCA increases a company's competitiveness and aids in operational excellence. It considerably increases speed and accuracy while also lowering the cost of carrying out LCA operations. Data traceability and transparency, made possible by blockchain technology, aid businesses in winning over customers' trust and loyalty, which can boost sales and improve market performance.

4.3. Payment Tokens

These are tokens in a blockchain that have a monetary value attached to them. Unlike traditional currency, these tokens can transact beyond geographical borders and business sectors and enable cross-platform collaboration between various supply chains. Bitcoin, Ethereum, and USDT are popular payment tokens.

Decentralized money transaction is perhaps the most widely known application of tokenization within supply chains. As shown in Figure 4, blockchain technology has allowed users to tokenize national currencies and transact them across borders without the need for central banks. This has opened doors to possibilities such as Initial Coin Offering (ICO), Decentralized Apps (DApps), Decentralized Autonomous Organizations (DAO), crowdfunding, and P2P funding.

Reduction in bureaucratic hassles is another plus point in using blockchain-based payment options. In sensitive industries with confidential data such as food quality labs, intellectual property (IP/patent) application, certain cosmetics, and, especially, food import/export, there are a lot of certifications and tests that need to be documented and verified before the concerned authorities. This ensures public health and consumer safety. Often this requires submission of sensitive data with third parties and lots of capital for hiring law firms to protect themselves and their firm. Smart contracts do not require the need for enforcers, third-party middlemen, banks, or lawyers. Instead, they require highly skilled programmers who can understand business logic and transfer them into the blockchain as code and an understanding of the legal nature of the asset that is being tokenized. The verification and consensus of health certificates, bill of lading, and letter of credit can all be converted into smart contracts using triggers and conditional clauses.

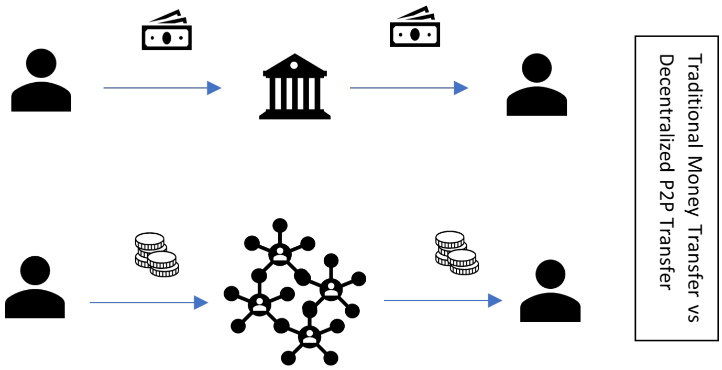

Figure 4. Traditional Payment System versus Blockchain-Based Payment System.

4.4. Automation

There is much potential for automation in the food systems with the introduction of blockchain. These include:

4.4.1. Decentralized Autonomous Organizations (DAO)

The acronym DAO, which stands for "decentralized autonomous organization," refers to a blockchain protocol that is open-source and controlled by a set of rules that were developed by its elected members and which automatically carry out specific tasks without the need for middlemen. The idea of a DAO was first put forth by Dan Larimer, the founder of BitShares, Steemit, and EOS (Block.one), in 2015. In 2016, Vitalik Buterin of Ethereum further developed the idea. We can segregate between smart contracts and DAOs in terms of automation and task complexity, as shown in Figure 5.

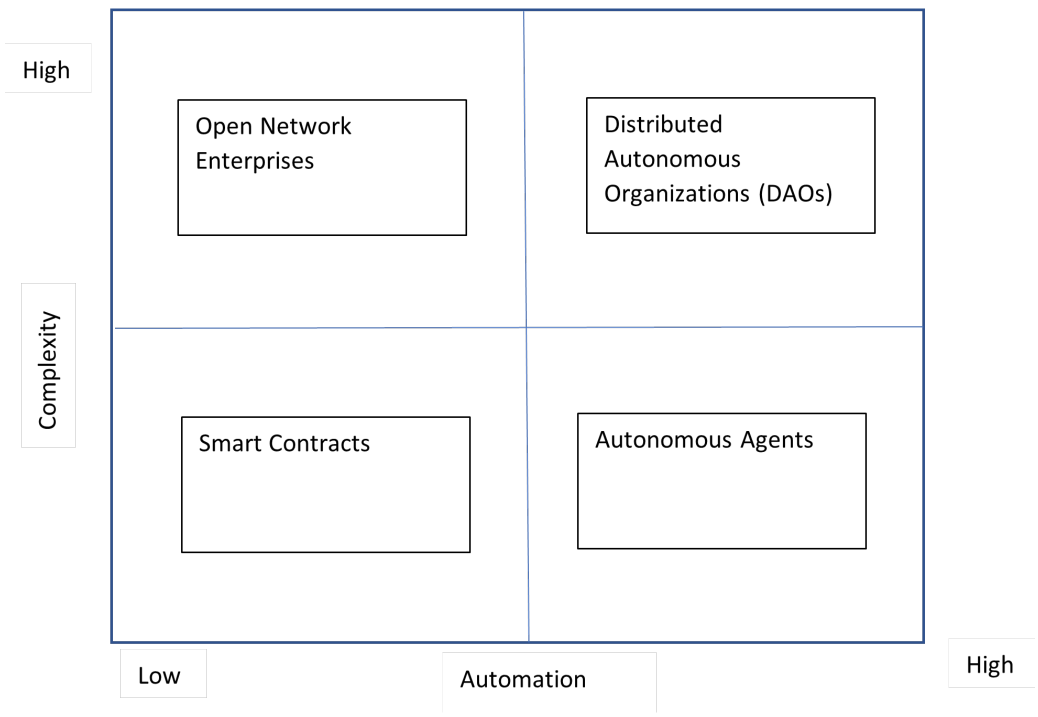

Figure 5. Task Complexity verses Degree of Automation Matrix.

The DAO's rules are contained in computer code, which, depending on how the protocol behaves, runs on its own. These program rules are automatically applied when the specified criteria are met; thus, there is no need to interpret them. A transparent and secure blockchain ledger that is distributed to network participants and immutably timestamped records both the program rules and subsequent actions. This ledger cannot be altered.

With the use of a DAO, a network can be kept secure and optimized without the need for manual intervention from its users. Participants are not obligated by a legal contract but rather incentivized by rewards in the form of native asset tokens that help them work towards a unified goal. The rules are defined by using a protocol or smart contract, and participants' actions are governed and automatically carried out. As no third parties are needed, a DAO helps to speed up network decision-making and actions and drastically lowers management costs.

4.4.2. Integration with Digital Twin Technology

A digital twin may be a virtual representation of a genuine item or a system utilized to comprehend and predict the operational highlights of its physical counterpart. Advanced twins are utilized to recreate, foresee, and advance the item and generation framework amid its lifecycle, prior to contributing in genuine models and resources. By coordinating multi-physics recreation, information analytics, and machine learning capabilities, computerized twins can outline the results of plan adjustments, utilization scenarios, natural components, and endless other factors. This deters the requirement for physical models, diminishes advancement time, and improves the ultimate item or handling quality. Advanced twins utilize real-time information accumulated from sensors connected to physical objects to assess their execution, working conditions, and changes over time. This guarantees exact modeling amid the product's life expectancy or make. Utilizing this information, a closed input circle is built up in a virtual environment, permitting businesses to ceaselessly upgrade their items, generation, and execution at a reduced cost. The computerized twin constantly evolves and upgrades to reflect any modifications made to the physical counterpart throughout the product's lifecycle. Depending on which stage of the item's lifecycle an advanced twin represents, a few applications may be conceivable. Computerized twins can for the most part be separated into three categories: item, generation, and execution. These categories are depicted below. The three computerized twins working together as a whole to advance the process is alluded to as the "advanced string".

5. Conclusions

In conclusion, we have provided an overview of blockchain technology with regard to the three pillars of food security and the effects of its adoption from various angles—consequently demonstrating that this is a young topic that offers crucial insights for the theory and practice of managing the digital food supply chain. While we have demonstrated the variety and complementary nature of the technology management science views used up to this point, we think there is still a need for more interdisciplinary and transdisciplinary research. Using additional technologies such as artificial intelligence and digital twin technology opens even more potential for innovation. Following the established and developing topical study clusters, we have specified various research issues. There appear to be certain untapped regions, though, which may result in new thematic clusters for blockchain adoption research on the digitization of food supply chains. The largest research gap identified in this literature review is the lack of studies conducted on the document processing of food certifications within the food supply chain transactions. Existing studies also ignore the role of international maritime/airtime food trade and the role of distributed ledger technology in such transactions.

- Lack of standardization: There is a lack of standardization in the development of blockchain-based solutions for maritime trade document processing, which can lead to interoperability issues between different systems.

- Legal and regulatory issues: There is a need for a clear legal and regulatory framework for the use of blockchain technology in maritime trade document processing. This includes issues related to data privacy, liability, and dispute resolution.
- Scalability: Blockchain technology is still facing challenges with scalability, which is a critical issue for large-scale systems such as international maritime trade.
- Adoption and integration: The adoption and integration of blockchain technology in the maritime trade industry is still in its early stages, and there is a need for further research on the practical challenges of implementing blockchain-based solutions.
- Cost-effectiveness: There is a need for research on the cost-effectiveness of blockchain-based solutions for maritime trade document processing compared to traditional paper-based processes.
- Interoperability with existing systems: There is a need for further research on how blockchain-based solutions can be integrated with existing legacy systems in the maritime trade industry.
- User acceptance: There is a need for research on user acceptance of blockchain-based solutions for maritime trade document processing, as well as the training and education required for users to effectively use these systems.

Issues such as farmer identity and farm work need to be studied from mathematical models and quantitative study methodologies. Moreover, more research needs to be conducted on the technology itself. As pointed out by Zhang, Yu, and Wen (2017) [9], blockchains have yet to be made efficient with regard to cybersecurity, consensus algorithms, interoperability, and scalability. The concept of a technology–strategy fit needs to be studied in the context of organizational behavior studies. Technology adoption problems are multifaceted, multidimensional difficulties that are influenced by various impediments. One must be aware of the problems and the barriers that impact these in order to create successful strategies for overcoming faculty usage of technology in instruction. This means that institutions must address both the barriers that affect stakeholders as well as the issues raised by those stakeholders. An institution can see the issues with integrating technology into teaching from a variety of angles thanks to the findings of the issue and barrier analysis. This leads to a deeper knowledge of the difficulties and makes it possible for institutions to create more effective programs to surmount these obstacles. Another aspect that needs to be considered is the knowledge management of technology. This includes the cost benefit analysis of adoption and the economic impacts of technology on the market and climate. Value chains may be reshaped in new ways thanks to innovative business strategies. The "circular economy" concept, for instance, aims to find ways for conventional "waste" streams to be transformed into a variety of value-added products through on-farm processing or start-ups launching platform technologies aimed at preventing food waste on the consumer end of (urban) food systems.

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Abbreviations

The following abbreviations are used in this manuscript:

AFN	Alternate Food Network
AFSC	Agri-Food Supply Chain
BCT	Blockchain Technology
CPI	Consumer-Producer Interaction
DAO	Decentralized Autonomous Organization
DApps	Decentralized Application
DLT	Distributed Ledger Technology
FLW	Food Loss and Wastes
FS	Food Security
FSC	Food Supply Chain
IAM	Identity and Access Management
ICO	Initial Coin Offering
IPFS	Interplanetary File System
LAFS	Localized Agri-Food System
LCA	Life Cycle Assessment
MRL	Maximum Residue Level
P2P	Peer to Peer
UA	Urban Agriculture

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