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Review

Blockchain-Driven Food Supply Chains: A Systematic Review for Unexplored Opportunities

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Abstract: This systematic review critically examines the diverse applications of Blockchain technology in the food supply chain and identifies areas where its potential remains underutilized. By analysing 60 Blockchain-based frameworks, the study highlights the most frequently employed drivers such as transparency, traceability, and security within food supply chains. Additionally, underexplored applications such as food donation and redistribution, supply chain financing, animal welfare, food waste management, and data analysis are identified, revealing opportunities for further innovation. The research employed NVivo 14 to analyze the extent of Blockchain's implementation in various food supply chain drivers, and the findings informed the development of a more diverse framework for Blockchain integration. Key insights demonstrate Blockchain's transformative potential, particularly in enhancing data integrity, trust, and operational efficiency through its immutable ledger and smart contracts, which streamline transactions, cut administrative costs, and reduce fraud. In terms of sustainability and safety, Blockchain improves traceability, accelerates safety responses, promotes environmental sustainability by tracking resource usage, and enhances humanitarian efforts with transparent, efficient resource distribution. Additionally, Blockchain facilitates food waste reduction by optimizing inventory and distribution, while ensuring surplus food reaches those in need. The study concludes by offering a roadmap for future research, pointing toward untapped dimensions of Blockchain's application in food traceability, sustainable supply chain management, and environmental & social impact. While the review provides a comprehensive understanding of Blockchain's current usage in food supply chains, the scope is limited by the systematic review process and specific inclusion criteria. This study serves as a foundation for exploring Blockchain's broader potential in shaping the future of food supply chains.

Keywords: Blockchain; Industry 4.0; precision farming; Agriculture 4.0; Livestock 4.0; food supply chain; smart waste management; animal welfare; supply chain finance; sustainability; circular economy

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1. Introduction

Food supply chains (FSCs) are characterized as being a collaborative network of mutually dependent organizations overseeing the movement of commodities and services in the refined chain of agricultural and food products [1]. This concept has evolved to encompass significant contributors to food safety and security, transforming FSCs into multifaceted systems involving consumers, farmers, manufacturers, distributors, retailers, and government agencies. Each stakeholder within the FSC plays a distinct role, contributing to the overall functioning of the system [2,3]. The primary objective of FSCs is to achieve excellent customer value while minimizing costs [1]. The processes within an FSC, including raw material production, processing, distribution, consumption, and disposal, are interconnected, resembling a domino effect where disruptions at one stage can trigger a sequence of events affecting the delivery of products to consumers. The interconnected nature of FSC operations emphasizes that any disruption in a particular step can have a ripple effect, impacting the entire supply chain [3,4].

Supply chain management is crucial in addressing food insecurity and public health concerns by integrating elements like the flow of information, warehouse and logistics, investments, and the trade of commodities and services. Establishing collaborative relationships among suppliers, producers, sellers, and consumers ensures dynamic and efficient operations. Modern supply chains have evolved into automated systems, providing significant benefits, such as cost reduction and operational efficiency.

In agricultural and food supply chain management, there is a strong emphasis on leveraging technological advancements to reduce losses and enhance quality control, particularly in terms of health and safety. Rigorous processes for monitoring quality and traceability have been implemented in response to the critical need for food safety and security following global foodborne incidents and food shortages. The increasing number of providers, globalization, and outsourcing in the food industry have added complexity to the supply system, prompting a demand for improved management solutions [5].

The globalization of the food trade has increased the complexity of food supply chains, leading to a higher risk of food fraud. This has resulted in diminished trust among supply chain stakeholders and heightened concerns about food safety among consumers [6,7]. The post-COVID-19 food supply system is marked by complexity, relying on multiple parties and facing challenges such as insufficient post-harvest storage, improper use of inputs, disrupted transportation, and processing facilities due to supply breakdowns from lockdowns and production interruptions. The global movement of food involves various transportation modes, introducing additional quality concerns, traceability issues, and transparency challenges. To address these issues, the integration of Blockchain technology into the logistics process was proposed to enhance the safety and quality of food. By incorporating Blockchain into the existing traceability framework, an improvement in the efficiency of food supply chains and greater consumer confidence could be achieved [8].

Various global food scandals, such as the 2008 China milk scandal, where milk adulterated with melamine to artificially increase protein levels led to illness in thousands of infants, have revealed critical gaps in supply chain oversight [9]. Blockchain technology can prevent such incidents by creating a transparent and traceable record of every step along the supply chain, ensuring quality control from farm to consumer. Key points in the supply chain, such as dairy farms, processing facilities, and distribution channels, could be recorded and verified through the Blockchain, ensuring that no harmful practices go unnoticed [10–14]. Additionally, the 2011 "food theft" scandal in India, the 2013 horsemeat scandal in the United Kingdom, and the 2013 egg contamination scandal in Europe and Hong Kong negatively impacted consumer trust in the food production system [9]. These incidents have underscored the need for greater transparency and effectiveness in food traceability systems.

A Blockchain, defined as a digital ledger with a series of blocks storing transaction records, offers inherent features like immutability, security, quality assurance, and transparency. These characteristics provide distinct advantages in terms of building trust within supply chains [15]. Additionally, Blockchain's use of smart contracts further contributes to enhancing trust [16]. Research suggests that a Blockchain can support various aspects of food supply chains, including food traceability, automation through smart contracts, food quality, and food safety [17].

The adoption of Blockchain technology in FSCs is exemplified by IBM's food tracking platform and Walmart's successful Blockchain pilot for pork supply in China [18]. The momentum for integrating Blockchains into FSCs is growing, with examples such as Albertsons joining the IBM Food Trust network in 2019, which already included major organizations like Walmart and Carrefour [19]. FSCs have been pioneers in exploring this distributed ledger technology, offering a solution for the efficient management of supply chain operations, with the food industry leading the way in implementing advanced initiatives utilizing Blockchains to enhance supply chains [20–22].

The significant growth of distributed ledger technology in the food industry offers an opportunity for theoretical and practical progressions in Blockchain-enhanced food supply networks. While previous comprehensive analyses of the applicability of this technology in food supply chains offer a strong foundation for scholars, the rapid evolution of this technology requires frequent updates so that its full potential in food supply chains can be fully realized. Thus, this review presents a more comprehensive framework for a Blockchain-driven food supply chain.

This study aims to examine various applications of Blockchain technology in food supply chains and pinpoint the areas within the food supply chain where these applications have yet to be fully utilized. Thus, it develops a comprehensive framework for a Blockchain-driven food supply chain.

As indicated in the literature review below, Section 2, the existing reviews concerning this topic have effectively addressed the subject. Nevertheless, the evolving landscape of the food supply chain has prompted a reevaluation of certain applications of Blockchain technology within the context of food supply chains.

The forthcoming systematic review aims to fill this gap by presenting a holistic and comprehensive overview of how Blockchain technology influences food supply chains. Additionally, it will identify opportunities by highlighting underutilized drivers, offering insights for future researchers to develop more effective and efficient Blockchain-based food supply chain systems. Additionally, to further complement our research objectives, this review proposes a framework to fulfill the essential need for a holistic and comprehensive understanding of a food supply chain driven by Blockchain technology. The suggested framework facilitates a straightforward, comprehensive application of Blockchain technology to food supply chains. It empowers upcoming researchers to delve into novel dimensions when applying Blockchain technology in this specific context.

2. Background

The application of Blockchain technology in the agri-food sector has garnered significant research attention in recent years, with a focus on enhancing food safety, transparency, and efficiency across supply chains. Bermeo et al. [23] explored Blockchain's role in agriculture, emphasizing its potential to improve food safety and transaction times while also noting the increased focus on Blockchain's use in food supply chains, particularly within the Asian research community. Additionally, the study highlighted the privacy and security challenges associated with integrating Blockchain and Internet of Things (IoT) technologies. Expanding on this, Zhao et al. [24] provided a comprehensive review of Blockchain's potential within agri-food value chains, identifying key challenges and research gaps. Their analysis advanced the understanding of Blockchain's role in enhancing food safety, traceability, and sustainable resource management, particularly in areas like water usage. Similarly, Peña et al. [25] focused on Blockchain's role in addressing food loss and waste in Ecuador's food supply chains. The study emphasized the need to combine Blockchain with IoT to enhance food supply chain management (FSCM).

Rejeb et al. [26] offered insights into Blockchain's transformative effects on the food industry, highlighting improvements in traceability, collaboration, and operational efficiency. Their review also pointed to technical, organizational, and regulatory challenges, providing a roadmap for future research. In line with this, Morella et al. [27] reviewed key Industry 4.0 technologies, including Blockchain, Big Data, and IoT, and their application in the agri-food supply chain, stressing the need for addressing scalability and security challenges. Chen et al. [28] provided a thematic analysis of Blockchain adoption in food supply chains, identifying critical themes such as adoption processes, benefits, and practical challenges, while Ahmad et al. [4] highlighted the growing preference for Ethereum-based Blockchain solutions to enhance food traceability, quality verification, and risk management. The latter also revealed the dominance of Ethereum as a platform for Blockchain-based traceability systems.

Exploring the synergies between Distributed Ledger Technologies (DLTs) and IoT, Nurgazina et al. [29] focused on their role in enhancing transparency, traceability, and sustainability in the food industry, linking Blockchain's adoption to the United Nations' Sustainable Development Goals (SDGs). Rocha et al. [30], in a review of Blockchain adoption in agribusiness, identified gaps between Blockchain prototypes and real-world applications, emphasizing the potential for improving supply chain reliability and agility.

Rana et al. [31], addressed Blockchain's role in sustainable agriculture, discussing its advantages and challenges in promoting sustainability across food supply chains. Dadi et al. [32] provided a broader perspective, highlighting digital technologies like AI, robotics, and Blockchain as enablers of innovation in the agri-food sector, enhancing supply chain efficiency and sustainability. Vu et al. [33] contributed a multi-layered model to guide Blockchain adoption in food supply chains, addressing adoption drivers, barriers, and applications. Their model offered a structured approach for practitioners in navigating the complexities of Blockchain integration. Srivastava et al. [34] built on this by providing a focused analysis of Blockchain applications in agrifood supply chains, proposing solutions for scalability and privacy challenges and enhancing food safety and traceability.

Other reviews, such as those conducted by Vistro et al. [35], Saha et al. [36], and Ali Taş et al. [37], also explored Blockchain's role in enhancing transparency, trust, and traceability in food supply chains. Vistro et al. [35] proposed a taxonomy for Blockchain integration, while Saha et al. [36] linked Blockchain's benefits to sustainability goals, including the triple bottom line (TBL) and net-zero objectives. Ali Taş et al. [37] utilized a system dynamics approach to assess Blockchain adoption in the complex, multi-stakeholder environment of food supply chains. Lastly, Subashini et al. [5] and Mohammed et al. [9] extended the discussion on food transparency and traceability, examining the performance of various Blockchain-based platforms and consensus algorithms. Mohammed et al. [9] provided a conceptual framework for Blockchain adoption, synthesizing enablers and barriers and offering evidence-based guidance for developing effective Blockchain strategies within food supply chains.

In summary, the literature consistently emphasizes Blockchain's potential to enhance transparency, traceability, and sustainability in agri-food supply chains. However, challenges such as scalability, security, and the integration of complementary technologies like IoT persist, highlighting the need for ongoing research and practical implementation strategies.

3. Materials and Methods

A systematic literature review (SLR) approach followed the methodology reported by recent scholars, exemplified by Liu et al. [38] in their application of systematic reviews to Blockchain-based governance and Jiang et al. [39] in their use of systematic reviews on Blockchain applications in waste management. The SLR is acknowledged as the pinnacle in review research methodology and involves a meticulous assessment and consolidation of prevailing research evidence in a targeted subject area. Employing a methodologically robust approach, these reviews offer a comprehensive and unbiased synthesis of information, serving as a valuable resource for decision-makers. Beyond guiding strategic decisions, they contribute significantly to advancing the collective understanding of a field by providing insights, identifying gaps, and fostering intellectual progress within academic and professional communities. Systematic reviews are foundational pillars in evidence-based practices, ensuring that the synthesized research contributes meaningfully to a given subject area's broader discourse and knowledge landscape [40].

As Pollock and Berge [41] recommended, the systematic review process involves a systematic search across databases to identify relevant studies, followed by meticulous selection based on inclusion and exclusion criteria. The extracted information is assessed for quality and risk of bias, ensuring the robustness of the evidence. The final stage involves synthesizing and presenting findings clearly and transparently, often using statistical methods like meta-analysis. This approach ensures methodological rigor at each stage, contributing to a comprehensive and reliable systematic review.

The guidelines established by Kitchenham and Charters [42] and Tranfield et al. [43], along with the widely recognized 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)', were integrated into this review. By adhering to these established frameworks, we aimed to uphold a rigorous and transparent methodology in synthesizing the expansive landscape of existing knowledge.

The adoption of PRISMA guidelines allowed us to present an organized and transparent account of our review process, facilitating a clear and reproducible methodology. Our systematic adherence to these robust frameworks aimed to address how Blockchain drives the food supply chain and contribute to the overall enhancement of scientific rigor and reliability of our systematic literature review.

3.1. Search Strategy

Scopus database functions as a comprehensive repository for abstracts and citations, widely employed in academic and research domains. In this study, it served as a search platform where the following search string was applied:

(TITLE-ABSTRACT-KEYWORD) ("Blockchain" OR "Decentralized ledger" OR "Cryptographic ledger") AND (TITLE-ABSTRACT-KEYWORD) ("Food" OR "Crops" OR "Agriculture" OR "Livestock" OR "Fruit" OR "Vegetable" OR "Meat".

3.2. Inclusion Criteria

It is noteworthy that while Blockchain technology originated in 2008, the literature focusing on the application of Blockchain in the food industry and the development of Blockchain-based food supply chain frameworks began to emerge in 2016, as indicated by our search criteria. Table 1 illustrates that, until 27 October 2023, 1821 records were identified in Scopus through the search string. However, only records written in English depicting frameworks for food supply chains based on Blockchain technology were considered in the final selection process (Supplementary Materials).

Table 1. Criteria and steps used in the current review following PRISMA (2009).

Identification	Records identified from Scopus: (n = 1821)	Duplicate records removed (n = 83)
	Records screened. (n = 1738)	1591 records were eliminated based on the absence of frameworks as indicated by abstract screening
Screening	Records sought for retrieval. (n = 147)	Records not retrieved. (n = 0)
	Records assessed for eligibility after thorough review. (n = 122)	62 Records were excluded because: • Full text did not include the food supply chain framework based on Blockchain (n = 62).
Included	Studies included in the review. (n = 60)	

3.3. Analysis of Concepts

This systematic review's goal is not solely to identify the key drivers of Blockchain adoption in the food supply chain; it also aims to pinpoint the underutilized drivers in this context. Hence, NVivo 14, a qualitative research tool, was employed to assess the extent to which these drivers were used across 60 publications in the systematic review.

The following steps were performed in NVivo 14:

- Textual content was queried using the keywords specified in Tables 2 and 3, enabling the identification of the number of publications utilizing these keywords, as indicated in the table below.
- A comprehensive review of each keyword was conducted by thoroughly examining all references associated with that keyword.

- Furthermore, only those references were included in the final count that explicitly cited the keyword as a driver for implementing Blockchain in the food supply chain.

4. Findings

4.1. Drivers of Blockchain Technology in the Food Supply Chain

"Drivers" refer to the factors or forces that push or motivate the adoption, development, or implementation of Blockchain solutions in various industries or applications. These drivers can be both internal and external, influencing the decision-making process of individuals, organizations, or governments regarding the utilization of Blockchain technology for specific purposes.

NVivo 14 was utilized to determine the extent of application across various aspects by multiple researchers on Blockchain in the food supply chain.

After thoroughly reviewing the 60 publications consisting of Blockchain-based food supply chain frameworks, several drivers were identified as follows:

- Donation and redistribution;
- Supply chain financing;
- Animal welfare;
- Food waste;
- Data analysis;
- Environmental and food sustainability;
- Accurate, authentic, reliable, secure, and trustworthy data;
- Automation and reduction in intermediaries;
- Cost-cutting, improved efficiencies, and reduction in frauds;
- Verifiability, auditability, accountability, and provenance;
- Food safety and quality;

These specific drivers in the food supply chain Blockchain have been extensively employed in over 40% of the publications (Table 2).

Table 2. Frequency and content analysis of drivers in Blockchain-based food supply chain frameworks reported in the literature.

Frequency and Content Analysis of Identified Abundantly Applied Drivers		
Total # of Blockchain-based food supply chain (FSC) *framework publications investigated*		*60*
Accurate, authentic, reliable, secure, and trustworthy data	# of publications discussing the usefulness of Blockchain for accurate, authentic, reliable, secure, and trustworthy data in the FSCs.	60
Traceability, transparency, tracking and monitoring	# of publications discussing the usefulness of Blockchain for Traceability, transparency, tracking and monitoring in the FSCs.	53
Cost cutting, improved efficiencies, and reduced frauds in the food supply chain	# of publications discussing the usefulness of Blockchain for cost-cutting, improved efficiencies, and reduction in frauds in the FSCs.	43
Automation and reduction in intermediaries	# of publications discussing the usefulness of Blockchain for automation and reduction in intermediaries in the food supply chain FSCs.	32
Verifiability, auditability, accountability, and provenance	# of publications discussing the usefulness of Blockchain for verifiability, auditability, accountability and provenance in the food supply chain FSCs.	28
Food safety and quality in the food supply chain	# of publications discussing the usefulness of Blockchain for food safety &and quality in the food supply chain FSCs.	27
Environmental and food sustainability	# of publications discussing the usefulness of Blockchain for Environmental and food sustainability in the FSCs.	21

The drivers of Blockchain in the food supply chain that have seen limited adoption are presented in Table 3.

Table 3. Frequency and content analysis of drivers scarcely applied in Blockchain-based food supply chain frameworks reported in the literature.

Frequency and Content Analysis of Scarcely Applied Drivers		
Total # of Blockchain-based food supply chain (FSC) *framework publications investigated*		*60*
Donation and Redistribution	# of publications discussing "Donation or Redistribution" as a driver of Blockchain in the FSCs.	2
Supply Chain Financing	# of publications discussing "Supply Chain Financing" as a driver of Blockchain in the FSCs.	3
Animal Welfare	# of publications discussing "Animal Welfare" quoted as a driver for Blockchain in the FSCs.	3
Food Waste	# of publications discussing "Food waste" as a driver of Blockchain in the FSCs.	4
Data Analysis	# of publications discussing "Data Analysis" as a driver of Blockchain in the FSCs.	6

4.2. Significance of Underutilized Drivers of Blockchain Technology in the Food Supply Chain

This systematic review focused on identifying the primary factors driving Blockchain adoption in the food supply chain and aimed at identifying underutilized drivers in this context. Therefore, we utilized NVivo 14, a qualitative research tool, to evaluate the prevalence of these drivers across the 60 publications in the systematic review.

It is important to note that the identified drivers' limited application in Blockchain-based food supply chain frameworks does not diminish their importance. These applications may be relatively scarce currently because Blockchain technology is still evolving. Nevertheless, these identified scarce drivers could offer upcoming researcher's new dimensions to focus on, potentially leading to the future development of more capable Blockchain-based food supply chain frameworks.

- **Significance of Transparent Donation and Redistribution**

The Food and Agriculture Organization of the United Nations anticipates that by 2030, around six hundred million people will be subject to experience persistent malnourishment, underscoring the substantial obstacle in achieving the Sustainable Development Goal (SDG) of eliminating hunger [44]. Food waste poses a considerable challenge in several countries, further compounding the issue. An innovative approach to address both concerns could be employing Blockchain technology to facilitate food donations and distribution [45].

Moreover, it is to note that recent wars, such as in Ukraine and Palestine, are having devastating effects on food security; Ukraine is presently confronting one of the swiftest instances of forced population displacement since World War II, with over 5 million individuals internally displaced and nearly 8 million refugees scattered across Europe. Approximately one out of every three families, around eleven million people, have no security for their food, and unemployment affects nearly one-third of the population. The bitter winter is posing additional challenges, leaving many without power. Furthermore, the presence of mines on the ground and debris from war disasters has rendered most of the land unsuitable for agriculture, significantly impacting the major food suppliers in the world. The repercussions of such atrocities have had far-reaching and destructive effects. This has led to a surge in overall inflation, thus further accelerating malnutrition and food availability hunger in third-world countries [46].

The Gaza Strip is currently experiencing severe levels of acute food insecurity because of ongoing hostilities, which include a severe military operation. According to the Integrated Food Security Phase Classification (IPC) report of 2023, eighty-five percent of the population, totaling 1.9 million individuals, have been displaced and are confined to a restricted area. The period from 8 December 2023 to 7 February 2024 saw the entire population, estimated at approximately two million people, classified at IPC Phase 3 or above, representing the highest percentage documented by the IPC initiative for acute food insecurity. Within this population, fifty percent, or 1.17 million people, are categorized as Emergency (IPC Phase 4), while over half a million individuals are designated as Catastrophe (IPC Phase 5). These individuals are facing severe food shortages, starvation, and depleted coping mechanisms, as outlined by the 2023 IPC report.

The UN World Food Programme (WFP) Innovation Accelerator and the Global Blockchain Business Council (GBBC) have joined forces through a Memorandum of Understanding (MOU) to launch 'Food for Crisis'. This collaborative initiative, supported by prominent entities like Accenture, Bayer, and others, aims to raise, track, and trace donor funds using digital technologies, particularly Blockchain. 'Food for Crisis' seeks to innovate humanitarian aid delivery to combat the global hunger crisis effectively. This initiative is expected to contribute to a more sustainable future by leveraging Blockchain technology for humanitarian purposes [47].

The United Nations World Food Programme (WFP) is the largest humanitarian organization globally, and it leads in delivering Blockchain-enabled cash transfer support. As a pioneering entity in adopting Blockchain technology within the humanitarian and developmental realms, WFP continues to seek innovative opportunities to set new standards in our pursuit of the 'Zero Hunger' goal. Building Blocks, a corporate initiative of the World Food Programme (WFP), is the humanitarian sector's most extensive cash distribution system based on Blockchain technology. It utilizes Blockchain for secure and efficient coordination with fellow humanitarian organizations, enabling the safe and efficient transfer of cash assistance to refugees [48].

Additionally, the Food and Agriculture Organization (FAO) approximates that around one-third of the world's food intended for human consumption is squandered or discarded, resulting in a significant economic setback. This loss impacts not just food producers and sellers but also consumers, with the annual financial toll of this discarded food reaching hundreds of billions of dollars [49].

- **Significance of Food Waste**

The Intergovernmental Panel on Climate Change, a body by UNO (IPCC), has recognized that food waste exerts considerable influence in increasing emissions of greenhouse gasses. As food decomposes in landfills, it emits methane, a powerful greenhouse gas that worsens the effects of climate change. To address the environmental impacts of our food systems, it is essential to prioritize reducing food waste and track compliance with strategies for reducing greenhouse gas emissions [50].

To cater for these issues, the global consulting firm Boston Consulting Group suggested that an extensive utilization of digital supply chain technologies has the potential to annually cut down food loss and waste by a staggering USD 120 billion [51]

Among several Blockchain-based projects on food waste, IBM Food Trust is considered a pioneering example. The IBM Food Trust is a Blockchain-based project that creates a secure, collaborative ledger for food waste management. It enhances transparency and trust across the entirety of the food supply chain, spanning from produce to consumption. The Insights capabilities module provides unparalleled visibility into the supply chain, aiding in pinpointing instances and locations of food waste. In contrast, the Trace module empowers participants by providing a secure and transparent method for tracking the whereabouts and condition of food products along the supply chain, enabling improved management and reduction in food waste [52].

- **Significance of Supply Chain Finance**

Additionally, the United Nations World Food Programme (WFP), European Multidisciplinary Platform Against Criminal Threats (EMPACT) stands out as a project dedicated to leveraging Blockchain technology to enhance supply chain finance within the food supply chain. The EMPACT project consistently grapples with a significant challenge where many young people in African nations lack access to traditional banking services. It is estimated that as many as 75 percent of Sub-Saharan Africans face financial exclusion, i.e., are devoid of formal financial institutions, credit options, and even basic savings accounts. While cash transfer platforms provide an alternative, they come with high transaction costs, rendering the receipt of payments for microwork both financially burdensome and time-consuming. The EMPACT project provides access to digital cryptocurrency-based accounts and mobile devices for microwork, enabling students to engage in activities directly from their smartphones, receiving payments with minimal transaction fees [53]

- **Significance of Animal Welfare**

A study conducted by Cornish et al. [54] reveals that people lack a solid understanding of animal welfare in the food supply chain. Emphasizing the potential of public concern to drive change, the authors propose widespread awareness efforts to develop acceptable methods for society concerning food extraction and production through animals.

The Organisation for Animal Health (OIE) currently serves as the sole trend-setter for veterinary issues, prioritizing animal welfare through the Terrestrial Animal Health Code defined by OIE. Animal welfare is based on scientific evidence, as per OIE, considering factors such as well-being, ease, sustenance, security, and the capacity to demonstrate natural behaviors. Farmers' attitudes towards positive animal interactions significantly impact animal welfare and productivity. Positive relationships, like animal stroking, have been shown to enhance positive affective states and improve production. On the contrary, using aversive handling methods, like pushing, is linked to diminished animal welfare and negatively impacts meat quality. Studies indicate that farmers' attitudes can be improved through improvised training, leading to promising results for animal welfare [55–59]

Recent research by Schillings et al. [60] highlights the potential of Digital Livestock advancements to enhance animal welfare. These technologies facilitate discussions among stakeholders and promote improved management strategies. Digital Livestock Technologies encouraged enhanced management strategies by fostering contemplation regarding the significance of animal emotional wellness and the creation of new paradigms for embracing positive attitudes leading to animal welfare. Schillings et al. [60] emphasized for Digital Livestock Technologies to truly advance animal welfare, it is crucial to prioritize those that contribute to a deeper insight into multiple angles of animal welfare and that reshape values and beliefs concerning the significance of animal welfare.

5. Discussion

Blockchain has much potential to be explored as it can drive the food supply chain in multiple ways that will be discussed in this section; based on our findings, there are several unexplored opportunities such as food donation and redistribution, food supply chain finance, food waste management, animal welfare, and data analysis. Now, limited adoption of these drivers is available in various Blockchain-based food supply chain frameworks. Therefore, our research highlights some significant drivers yet to be utilized and will empower future researchers to explore new avenues for the application of Blockchain technology within the context of the food supply chain.

As emphasized in the preceding section, the importance of food donation and redistribution, food supply chain finance, food waste management, and animal welfare cannot be overlooked. The absence of these factors in Blockchain-based frameworks for food supply does not imply their insignificance; rather, it underscores the need for researchers to incorporate these dimensions to create more comprehensive and practical frameworks.

5.1. Most Common Drivers for the Application of Blockchain Technology in the Food Supply Chains

- **Accurate, authentic, reliable, secure, and trustworthy data**

Traditional inventory systems and manual record-keeping methods in supply chains can result in errors, information disparities, and unreliable information [61]. This can lead to mislabeled products, low traceability, and trouble initiating recalls for defective or expired items. Blockchain technology stores all transactions and events throughout the supply chain in a decentralized, transparent, auditable, and tamper-proof way, ensuring information accuracy and trustworthiness [61].

Blockchain technology impacts the brand's security by ensuring authentic food items reach consumers rather than counterfeits. This technology is superior to conventional methods, such as paper-based documents or certificates or barcodes that are unable to act as a reliable and secure source of information as these can be quickly counterfeited [62,63].The credibility of high-value food items from reliable brands or those that include special bioactive ingredients is ensured by the unalterable and transparent ledger that Blockchain technology maintains for every single transaction. A unique identifier on a Blockchain can be created based on the input of essential information in the Blockchain ledger. These identifiers can be certificates, test outcomes, and quality examinations. Blockchain-based tamper-proof identifiers enable the verification of legitimacy and provide a reliable method to validate manufacturing processes and inventory cycles [62,63],

Smart contracts based on the set criteria may define conditions for dealing with, reasonable trade practices, or qualification of authenticity (e.g., organic product and slaughtering methods); if such requirements are not complied with, further activity of the item across the chain might be restricted. This guarantees that only genuine and lawful items reach the marketplace [64].

By utilizing its inherent attributes, Blockchain technology has enhanced accountability within the food supply chain. Every purchase, ownership change, and product condition change might be safely recorded in a decentralized ledger. Stakeholders can follow and validate the circulation of food goods at every level of the supply chain. It has now become simple to identify any efforts at fraud or unauthorized alterations, encouraging accountability and preventing unethical behavior [12,65] (Figure 1).

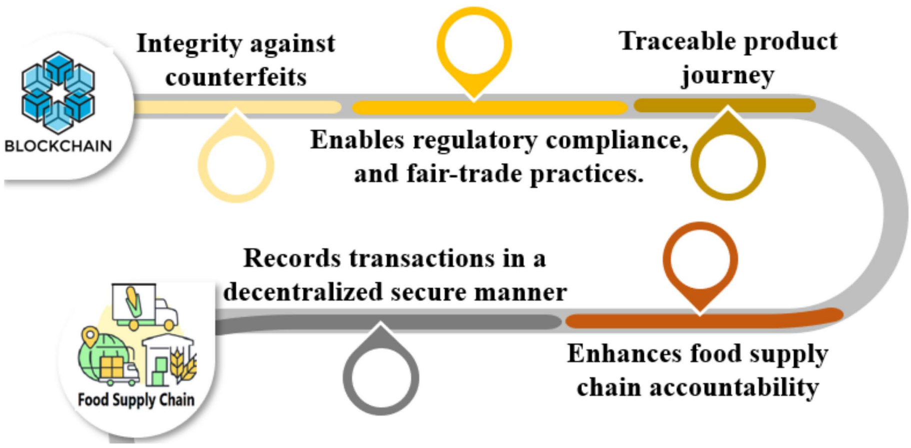

Figure 1. Blockchain application in food supply chain (accurate, authentic, reliable, secure, and trustworthy data).

- **Automation and reduction in intermediaries**

Several food supply chain processes, such as payments or return settlements, quality checks, and conformity audits, may be automated with the aid of smart agreements, which are self-executing contracts with predetermined rules and conditions. Therefore, there is no more requirement for intermediaries like financial institutions or outdoor auditors. An illustration of automation through Blockchain can be seen when a farmer offers vegetables to a supplier. Upon the representative receiving and inspecting the items, smart contracts can promptly initiate the payment to the farmer. This reduces the risk of payment delays or disputes and eliminates the need for conventional payment methods [66–68].

Furthermore, the application of Blockchain technology in an automated watering system guarantees exact water distribution for every crop, lessening wastage and maximizing yields. By utilizing Blockchain, it becomes practical to keep track of and record water usage, guaranteeing each plant receives the optimal quantity of water. This aids in decreasing water wastefulness and making the best use of plant yield. Moreover, it enhances data administration and openness within smart irrigation systems, approving all stakeholders' access to specific and live water usage details [69] (Figure 2).

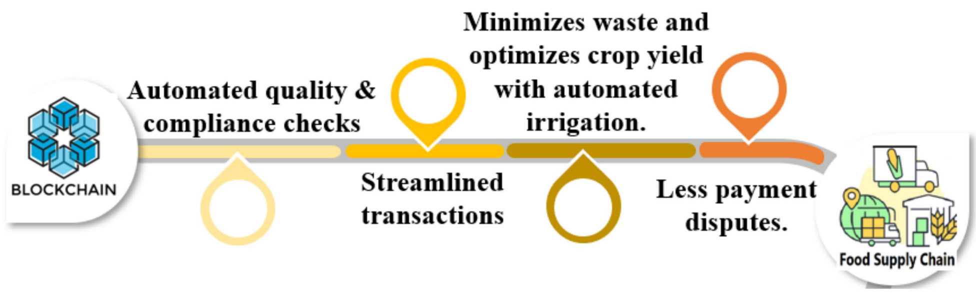

Figure 2. Blockchain application in food supply chains (automation and reduction in intermediaries).

- **Improved traceability, transparency, tracking, monitoring, and response times**

Blockchain technology significantly improves traceability, transparency, tracking, monitoring, and response times within the food supply chain. The Blockchain-based ledger, integrated with the network and IoT sensors, provides real-time updates accessible to all stakeholders. Each stakeholder can access and update relevant details, facilitating real-time problem-solving and decision-making. This leads to enhanced stock management, streamlined logistics, and improved individual coordination, as highlighted by Yadav et al. [17].

This improved traceability, transparency, tracking, and reaction times result in better troubleshooting and problem identification, and recalls are much less complex and quicker when there is a food safety and security threat located [70]. This permits targeted recalls, reducing waste and minimizing the impact on consumers [13,14]. Finding the source is much easier and quicker regarding an epidemic or contamination of a foodborne illness. Authorities and stakeholders might quickly locate the trouble's source and acknowledge impacted batches and production lots by utilizing the transparency of Blockchain. Clients may likewise obtain comprehensive information on the items they purchase, including their origin, active ingredients, allergic reactions, and nutritional realities. This allows people to choose based on their tastes and dietary needs [14].

Enhanced transparency and traceability allow for keeping track of ecological conditions by recording relevant information, such as temperature and moisture, on the Blockchain, thus helping prevent spoilage and food waste [71]. Monitoring factors such as temperature, humidity, location, and quality standards are possible through the combination of Blockchain with Internet of Things (IoT) gadgets and sensors [72]. Because of this integration, any deviations from the specified standards might be quickly recognized, permitting quick mistake modification and decreasing succeeding troubles. Throughout the food supply chain, IoT gadgets (sensing units, RFID tags), smart contracts, and Blockchain are capturing and saving real-time information [72]. The interoperability of sensors with Blockchain enables tracking conditions (such as food location, temperature, moisture, and pH levels) during product movement and storage. In case of any deviation from the required conditions, specific relevant actions or warnings are activated [14,73,74]. Inevitably, improved traceability, transparency, tracking, monitoring, and response times through Blockchain will boost the handling and tracking of disposable products, guaranteeing fresher and much safer products and enhancing the overall food supply chain (Figure 3).

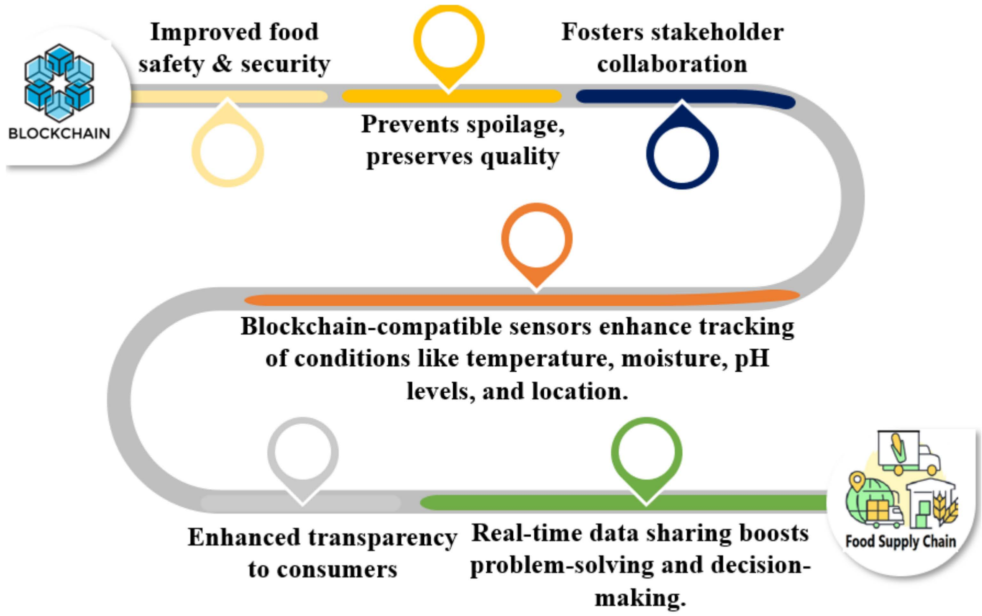

Figure 3. Blockchain application in food supply chains (improved traceability, transparency, tracking, monitoring, and response times).

- **Verifiability, Auditability, Accountability and Provenance**

Enhanced traceability throughout the food supply chain creates an accurate and auditable trail of food products, such as ingredients' origins, manufacturing procedures, quality checks, accreditations, or inspections undertaken, and the scenarios under which they were transported and kept [14].

Information stored through Blockchain is immutable and unalterable, and it spans the entire food supply chain, from the purchase of components and production procedures to shipping and storage space. This enables an improved system of auditability by reducing the chances of mistakes by auditors as they receive more accurate information than manual data collection. An examination of information related to the transaction, such as timestamps, including stakeholders and events, and related documents, through using the Blockchain not only makes the auditability accurate but also leads to efficient operations and better control. Blockchain may additionally synergistically work with Internet of Things (IoT) devices, sensors, and other information-gathering tools to collect real-time information on critical elements like temperature levels, moisture, and locations in the food supply chain. The Blockchain automatically stores this information, providing auditors access to exact and existing data. Real-time data events ensure that audits are accomplished promptly and help auditors quickly see potential issues [70,75].

Additionally, smart contracts through Blockchain technology enable better monitoring and tracking of activities and events throughout the food supply chain. These contracts would enable auditors to validate information related to compliances, thus improving audit efficiency and effectiveness [10].

Modern Blockchain technology offers a reliable, safe, and secure database for electronic certificates, conformity details, and audit reports, offering a tamper-proof record of certifications and audits. This enables regulatory authorities and auditors to successfully confirm compliance with food safety and security guidelines and laws while certifying organizations can be given access to the Blockchain to release and upgrade certifications, improving accountability while doing so [76]. Additionally, Blockchain enables the traceability and provenance of food products by saving vital info such as the origin of products, manufacturing procedures, quality control procedures, and transport-specific problems. This enables regulators, auditors, and customers to verify the credibility and purity of food easily, and in case of any kind of concerns, the liable party can be promptly identified, promoting accountability for non-compliance or misbehavior [10–14] (Figure 4).

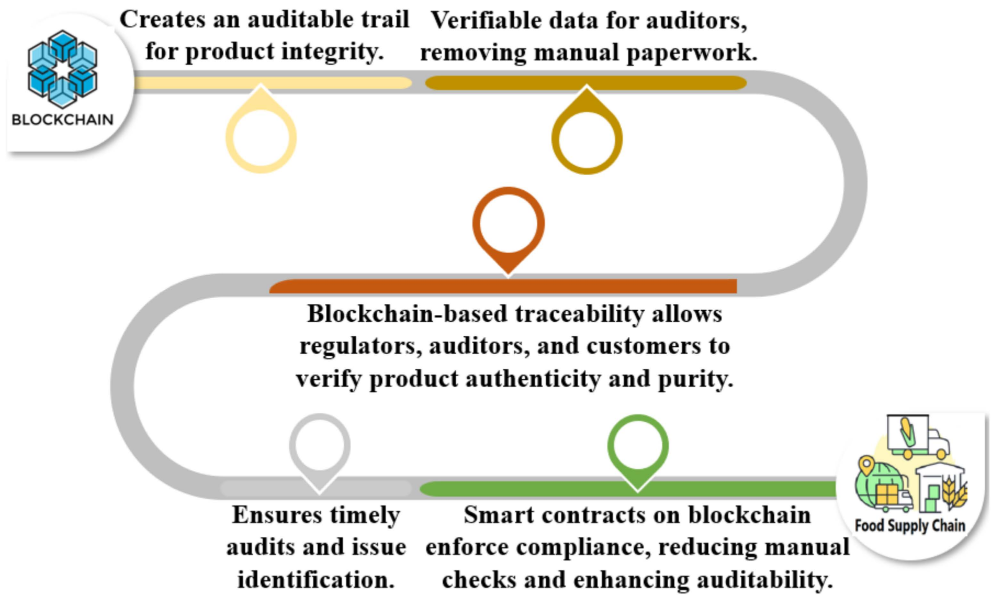

Figure 4. Blockchain application in food supply chain (verifiability, auditability, accountability and provenance).

- **Cost cutting, improved efficiencies, and reduction in frauds in the food supply chain**

The ability of Blockchain to provide information about real-time activities throughout the food supply chain empowers stakeholders to make data-driven choices, streamline planning, and coordinate initiatives perfectly, thus resulting in fewer delays, replications, and inadequacies, inevitably leading to financial savings and a lower risk of fraud [14] Additionally, the enhanced transparency through Blockchain technology has resulted in no need for third parties and the use of middlemen. This technical advancement has significantly reduced the management expenditures connected with paperwork, information reconciliation, and interaction between parties. The data from stakeholders are more accurate and reliable; therefore, many of the procedures and activities in the supply chain, such as purchase verification and data sharing, are streamlined, thus enhancing operations and resulting in cost efficiencies [77,78].

Additionally, Blockchain's real-time traceability would enhance inventory management and enable stakeholders to optimize supply replenishment, decrease overstocking and understocking, and reduce storage expenditures. The continuous tracking of inventory movement will result in supply chain efficiencies, thus resulting in cost savings [63]. This automation reduces payment cycles, minimizes settlement disputes, decreases transaction prices, and streamlines financial transactions. This helps reduce costs and manage cash flow better [79,80]. Furthermore, it reduces the risk of deceitful operations, unauthorized record adjustments, and imitation products by recording all deals and assuring information integrity. With less risk, less money will be spent on product recalls, legal issues, and brand name damage [81] (Figure 5).

- **Food safety and quality**

Blockchain technology guarantees food security and top quality. It offers end-to-end traceability and tracking within the food supply chain. This permits real-time tracking of ecological variables that impact perishable items, enabling stakeholders to verify correct storage and transportation conditions, thus preserving quality and decreasing spoilage [71].

Blockchain innovation makes it possible to complete the recording and recognition of a food's whole supply chain, from where it was grown to the consumer. Using this capability, polluted or hazardous things may be quickly recognized and included, accelerating targeted recalls and minimizing the spread of foodborne diseases. Stakeholders may conveniently examine the accuracy and legitimacy of certifications by saving such information on the Blockchain, guaranteeing that the food fulfills the essential safety and security requirements [66,81] (Figure 6).

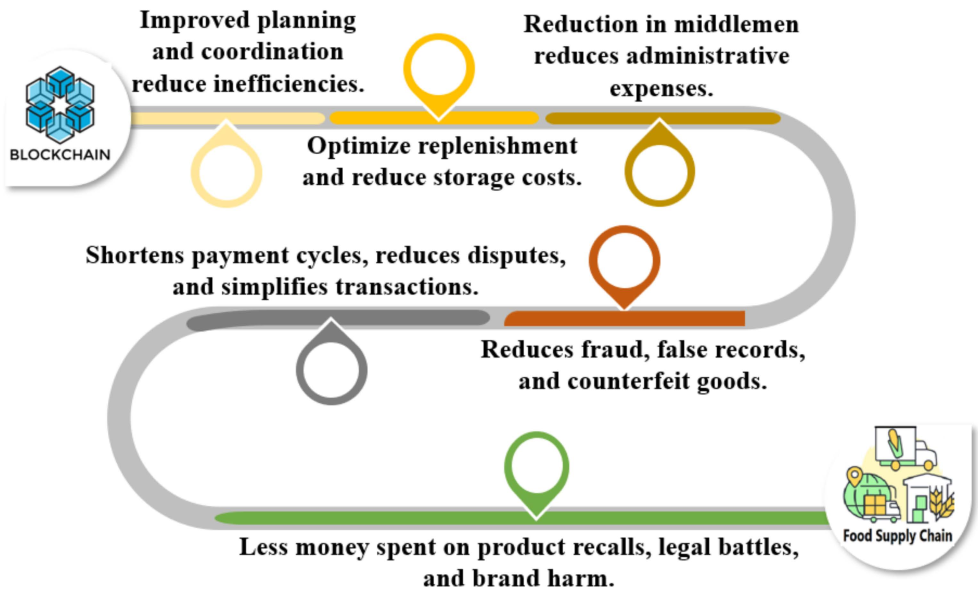

Figure 5. Blockchain application in food supply chains (cost cutting, improved efficiencies, and fraud reduction.).

Figure 6. Blockchain application in food supply chain (food safety and quality).

- **Environmental and food sustainability**

Blockchain technology makes it possible to track waste, unethical behavior, and unsustainable practices in the food industry through real-time monitoring and transparency, assisting stakeholders in making far better decisions for the setting. With accessibility to reputable information, stakeholders can optimize their sourcing, transport, and waste administration choices, ultimately decreasing their environmental footprint [63].

Blockchain technology allows for the recording and verification of certifications for sustainable sourcing methods, such as organic, fair trade, or eco-friendly labels. This supports suppliers that follow eco-conscious practices and promotes responsible sourcing. Subsequently, the information can be provided to customers on eco-friendly and ethical food manufacturing [66].

The measuring and monitoring of carbon footprints connected to food manufacturing and transportation can likewise be implemented using Blockchain technology. Pertinent information on energy use, pollutants, and other environmental parameters may be securely stored by incorporating IoT gadgets and sensing units with the Blockchain. This knowledge allows interested stakeholders to take data-driven actions to reduce carbon exhausts and check out prospective carbon-balancing projects. To lower the adverse effects on the environment, Blockchain innovation can also be utilized to optimize the use of pesticides, fertilizers, antibiotics, and watering [82]. Blockchain likewise urges environmental sustainability by enhancing adherence to environmental regulations [82]. Allena et al. [83] argued that Blockchain might effectively keep track of conformity with ecological criteria by getting rid of corruption and harmful administration by proactively entailing regulators and the public (Figure 7).

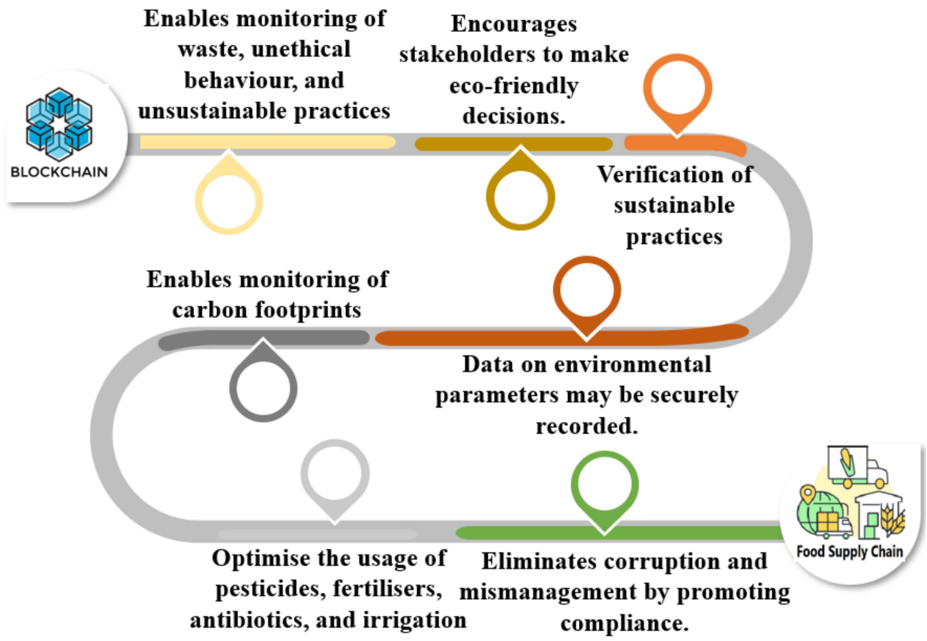

Figure 7. Blockchain application in food supply chains (environmental and food sustainability).

5.2. Scarce Drivers for the Application of Blockchain Technology in Food Supply Chains

- **Donation and redistribution**

The Food and Agriculture Organization of the United Nations forecasts that by 2030, approximately six hundred million people will still experience chronic undernourishment, posing a significant obstacle to achieving the Sustainable Development Goal of eradicating hunger [44]. In 2022, around seven hundred and thirty-five million individuals, accounting for 9.2% of the global population, suffered from chronic hunger, a notable increase from 2019. Additionally, an estimated 2.4 billion people grappled with moderate to severe food insecurity in 2022, indicating insufficient access to nourishment, with a rise of 391 million people compared to 2019 statistics, according to the United Nations [84].

Additionally, it is important to highlight those ongoing conflicts, exemplified by those in Ukraine and Palestine, are significantly impacting food security. Ukraine is currently undergoing one of the swiftest forced population displacements since World War II, witnessing over five million internal displacements and nearly eight million refugees in Europe. In the Gaza Strip, acute food insecurity has reached catastrophic levels due to hostilities, including bombardments and ground operations, leading to the displacement of 85 percent of the population (1.9 million people) concentrated in a confined space [46,85].

Throughout the World Food Programme's existence, humanitarian aid typically involved direct delivery of food, clothing, or sanitary products, resulting in substantial costs and logistical distribution challenges. Recently, financial assistance for refugees has shifted towards utilizing vouchers or prepaid debit cards, 2017). Through these cash-based transfers, WFP supports over 14 million people, constituting approximately 15% of the total population assisted by the UN agency [48].

Humanitarian cash-based transfers from WFP allow recipients to buy essential items from stores, reducing transaction costs and improving poverty reduction, health, and nutrition. These activities stimulate economic growth that could lead to less dependence on aid. Cash-based transfer systems face challenges, particularly for refugees who frequently travel long distances. The loss of vouchers or credit cards can lead to information asymmetry, making it difficult for food distributors to verify refugees' identities and grant them access to resources, as Bastagli et al. (2016) noted [86].

The WFP launched a Blockchain initiative, "Building Blocks," to help over 100,000 refugees in the Azraq camp in Jordan receive cash-based transfers for basic goods [44]. The project aimed to increase efficiency and streamline financial processes by leveraging digital identities and bypassing local intermediaries. Development took less than five months. Blockchain technology was used in the Building Blocks program to distribute cash to refugees without costly verification processes. Vendors used a Blockchain wallet to receive payment directly from WFP. Building Blocks used Blockchains, digital databases, and biometrics for identification. In addition to its potential to stimulate economic growth, the technology saved USD 150,000 per month by eliminating 98% of bank fees [48].

The World Food Programme (WFP) focused on providing food assistance to conflict-affected regions, offering a lifeline to those affected by violence. The WFP's innovative cash and voucher programs empowered displaced populations to purchase food locally [48] (Figure 8). The World Food Programme (WFP) has been crucial in addressing humanitarian crises in Pakistan, Syria, Ukraine, Bangladesh, Jordan, and Lebanon (Figure 9).

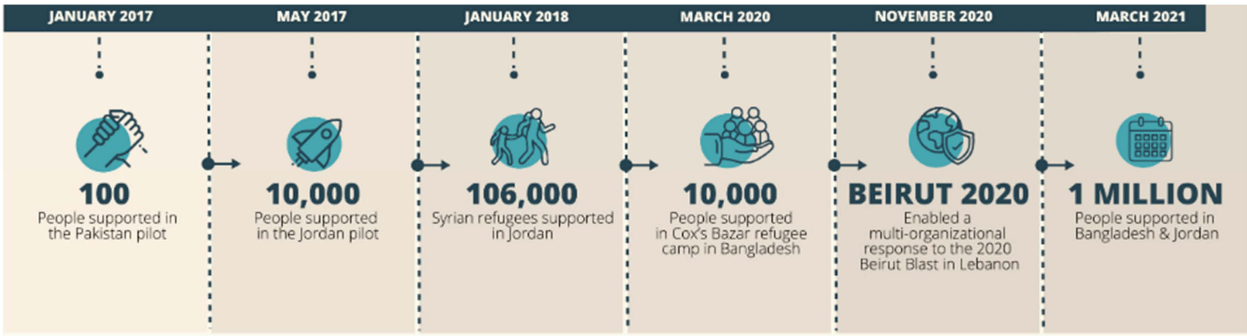

Figure 8. Number of refugees supported by building blocks [48].

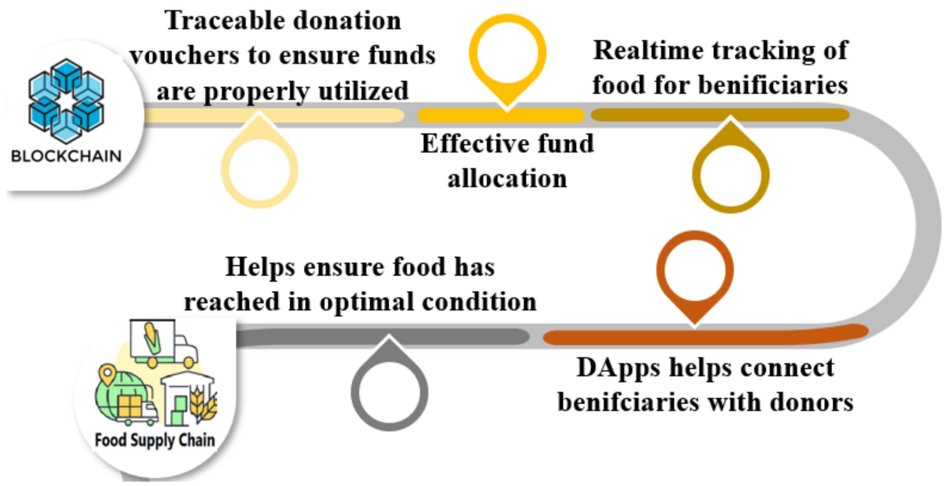

Figure 9. Blockchain application in food supply chain (donation and redistribution).

Charities lack transparency, leading to loss of trust and stagnant funding. Donors are unaware of the legitimate utilization of funds, and this lack of transparency could lead to corruption [87]. Elavarasan and Nesakumar [88] and Krishnan et al. [89] created two Android apps to connect donors with the needy. Quick response codes were used for data validation. Approximately 40% of food in the United States goes to waste, translating to an average American family squandering USD 1500 worth of food annually. This massive amount of wasted food is in landfills, contributing to greenhouse gas emissions and climate warming. Avoid becoming part of this statistic.

In Indonesia, orphanage foundations predominantly depend on independent donor management for funding, posing a challenge for donors to gain information about the orphanages entitled to support, especially regarding food supplies such as rice. To overcome this, Junfithrana et al. [90] proposed a solution—a Blockchain and IoT-based rice donation system for orphanages. This system incorporated robust IoT sensors to identify the available quantity and need of rice in each orphanage, connected via Raspberry Pi devices. Donors can utilize an application to monitor foster care conditions and identify orphanages with rice shortages. Transactions trigger suppliers to deliver rice to the specified destination, with smart contracts in the Blockchain network ensuring transparent and secure monitoring of all transactions.

Despite numerous studies and models aiming to enhance charity donation systems, concerns and suspicions persist among donors regarding charity-related transactions. The advent of Blockchain technology and its potential to promote trust and efficiency in charity donations, particularly in developing countries [91]. Other researchers Hamdani, [92] & Rejeb [93] explored the use of Blockchain in managing mandatory charity donations, specifically in Islamic practices like Zakat in Sharia, Zakat Almaal, translated as wealth purification, is a monetary donation of 2.5% of excess wealth to the needy. Also, there is Zakat El-fitr, translated as purification of breaking the fasting of Ramadan, which is a donation of grains to the poor). They proposed leveraging Blockchain technology to connect all parties involved through decentralized applications (Dapps) for increased reliability, utilizing self-executed smart contracts to automate the execution of regulations. The transparency of Blockchain allows donors to track their contributions from the point of donation through charity to the ultimate beneficiary, offering increased transparency and accountability in charity transactions [87]

In summary, the incorporation of Blockchain technology can potentially revolutionize and significantly improve the processes of donation and food distribution in humanitarian efforts. The transparency, traceability, and security features of Blockchain can build trust among donors, recipients, and implementing organizations. Smart contracts enable automated and transparent transactions, ensuring efficient delivery of donations. The immutability of Blockchain records reduces the risk of fraud and corruption, fostering accountability in the entire supply chain. Blockchain's decentralized nature can also streamline coordination among different parties involved in food distribution, reducing bureaucratic hurdles and enhancing response speed during crises. As technology progresses, the adoption of Blockchain in humanitarian initiatives holds promise for creating a more accountable, efficient, and equitable system to address global food insecurity and humanitarian challenges (Figure 9).

- **Supply Chain Financing**

Supply chain finance (SCF) focuses on facilitating fiscal resource movement among companies to optimize the flow of goods and services using financial instruments or technological solutions [94,95] This approach integrates financial transactions into the traditional aspects of supply chain management, emphasizing the efficient and timely exchange of information. This integration streamlines both the physical movement of goods and the movement of capital, resulting in reduced costs related to finance and risk management. Information flow is closely linked to the level of risks, which enhances the information processing capacity crucial for facilitating financial transactions and managing associated risks and uncertainties throughout the supply chain [96]

Blockchain technology, known for its decentralized, verifiable, and immutable characteristics, involves multiple parties collaboratively engaging in processes to create, store, and share specific verified information [97]

Innovative technologies have spurred the creation of modern models for supply chain finance (SCF). These platforms offer a holistic approach to SCF, connecting stakeholders and optimizing various processes such as ledger reconciliation, purchasing orders, generating invoices, processing payments and credit notes. Initially introduced by banks, technology-derived financial instruments are now provided by several service providers through these advanced supply chain finance platforms.

Hong [98] proposes that grain financial institutions utilize their expertise in the grain market and valuable insights into core corporate customers to strategically advance grain supply chain finance. The author suggests employing online platforms for loan application, review, and issuance to facilitate a seamless online grain supply chain financing process. Meanwhile, Natanelov et al. [99] examined the integration of Blockchain and smart contract technologies in the Australia–China beef supply chain, demonstrating their potential to enhance efficiencies by improving information, monetary, and physical asset movements. The study highlights the potential of Blockchain-based smart contracts to mitigate risk and reduce cash influx cycles in conventional supply chain finance models while also introducing novel models like intelligent financing and collective financing to delve into the transformative impact of Blockchain and smart contract tools on emerging supply chain finance innovations.

Financial institutions are urged to emphasize innovation in supply chain financing services, tailoring equity models to the developmental stage and financial needs of various agricultural sectors. Incorporating advanced financial methods, including custody and trust financing, is considered a strategy to drive rapid and healthy development in agricultural supply chains. Proactive innovation and a comprehensive understanding of supply chain dynamics are essential for financial institutions to thrive in the evolving rural grain financial landscape [98]. Distributed ledger technology, particularly Blockchains, can provide transparency for financial institutions, aiding informed lending decisions and reducing risks associated with financing across the food supply chain. Furthermore, integrating smart contracts into Blockchain technology automates and streamlines financial transactions, expediting payments and easing administrative burdens. This Blockchain-based supply chain finance enhances the food supply chain's resilience, responsiveness, and adaptability to market dynamics, potentially optimizing working capital, mitigating risks, and ensuring overall sustainability [98] (Figure 10).

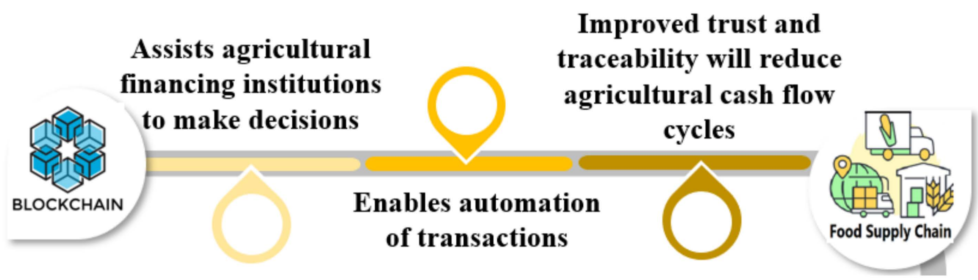

Figure 10. Blockchain application in food supply chains (supply chain finance).

- **Improved Animal Welfare**

Animal welfare and ethical food production are essential in the perception of the quality and marketing of a product. Blockchain technology encourages supply chain transparency by giving stakeholders the ability to track and verify the whole life cycle of animal products, including on-farm management (e.g., breeding, diet, veterinary and health care, and stress control) and off-farm management (transportation, animal handling, and processing conditions). This openness ensures that animals' welfare and production of animal-based products have been carried out ethically and under established guidelines for humane and ethical animal practices.

Consumers can make informed decisions about animal products with access to details on rearing conditions, medical histories, and welfare certifications [100]. Employing sensors to monitor animal behavior, biometric methods, artificial intelligence, and big data analytics can enhance breeding programs, selecting stress-resistant breeds [101]. Non-invasive techniques like measuring skin temperature and using Total Internal Reflection (TIR) of eye optics enable early illness detection, aiding disease management [101].

Blockchain's immutable ledger enables the secure storage of crucial details regarding animal lineage, breeding procedures, health status, vaccination history, and living conditions. This transparency facilitates accountability for any violations of animal welfare laws, as the clear and auditable record allows for the easier identification of offenders. By tracking the entire supply chain, instances of abuse or welfare issues can be promptly detected and addressed, ensuring greater responsibility and integrity in the management of animal welfare [100,102,103]. Intelligent livestock farming technologies improve animal well-being surveillance, enabling early detection of health issues before diseases emerge. By leveraging historical data and symptom records, these methods enhance livestock welfare, alleviate concerns about food safety, and optimize resource utilization. This fosters a more sustainable agriculture industry, promising a brighter future for future generations (Figure 11).

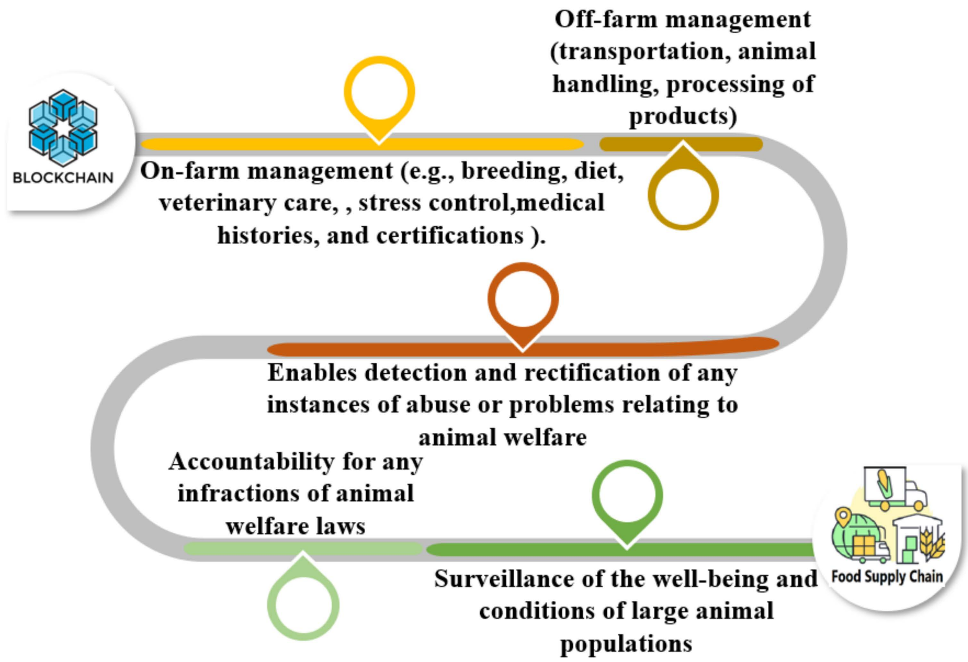

Figure 11. Blockchain application in food supply chains (improved animal welfare).

- **Food Waste**

Food wastage is a notable societal issue and an environmental concern. Each year, approximately a third of the world's total food production, equating to above one billion tonnes and valued at USD 2.6 trillion, is lost or wasted. Despite this, over 820 million people lack access to nutritious meals worldwide. Furthermore, food waste and loss contribute to nearly 6% of global greenhouse gas emissions, posing environmental risks [45].

Food waste refers to the decrease in the amount or quality of food occurring during the consumption phase, encompassing any remaining organic matter from food items suitable for human consumption disposed of following its entry into the operations of the food supply chain for further processing and subsequent consumption. Additionally, the broader term "overall biomass loss" includes losses of crop, livestock, and fish products throughout the food supply chain for various utilizations (food, feed, seed, other), excluding the retail-to-consumption level [104].

Sabine Valenga, and her co-founders David Rodríguez and Victor Carreño, conceived the idea for Food for All during a Harvard incubation program. This innovative app enables users to rescue food from restaurants an hour before closing at a significantly reduced cost. The app has established partnerships with numerous restaurants in Boston and New York City, with a mission to challenge and transform the prevailing food waste culture in America and beyond. The Food For All app connects donors with volunteers to deliver leftover food to the needy [105].

Blockchain technology offers a transformative solution for monitoring the movement of commodities and materials across the operations within the food supply chain, enabling the identification and mitigation of waste. An illustrative instance of its efficacy is highlighted in a World Economic Forum (2020) study, which suggests that the integration of Blockchain has the potential to curtail food wastage by an impressive 25%. Notably, major industry players such as Walmart have embraced Blockchain for tracing the path of food products from their initial production on the farm to reaching the end consumer, leading to significant advancements in waste reduction and enhanced food safety within the company's operations [106].

Abdullah et al. [107] suggested a waste management system based on the Internet of Things for smart cities, concentrating on the acquisition, disposal, and repurposing of waste in appropriate facilities. Similarly, Dubey et al. [108] proposed a waste management system based on the Internet of Things and artificial intelligence, managing waste generated at homes and societal levels in the city. Notably, both studies emphasized waste management rather than reduction, as Dey et al. [45] highlighted.

The study conducted by Dey et al. [45] investigated the integration of Blockchain and machine learning in addressing food waste in the food supply chain and smart cities. The researchers introduced SmartNoshWaste, a model with several layers based on Blockchain, cloud computing, QR codes, and artificial intelligence. This framework aims to minimize food wastage within decentralized smart cities empowered by Web 3.0. Through experimental evaluation using real potato data from the Nosh app, SmartNoshWaste demonstrated a 9.46% reduction in food waste compared to the existing waste recorded by the app.

In October 2016, Walmart and IBM collaborated on a Blockchain technology proof of concept to trace mangoes through the supply chain [18]. This study demonstrated the efficiency of Blockchain in quickly and accurately tracking food from the farm to the store. The key finding was that Blockchain significantly improved visibility into the speed of food movement, challenging the traditional practice of solely attributing issues to farmers. The proof of concept revealed specific insights, such as mangoes spending an extra four days at border control, which could be saved to extend shelf life, enhance product quality, and reduce food waste. Blockchain identified the supply chain inefficiencies, leading to a proactive "fact-finding" approach to addressing issues and ultimately resulting in better quality products and less food waste [18].

Improved transparency and traceability through Blockchain facilitate accurate recalls, reducing the discard of uncontaminated food and enhancing public health safeguards. This approach, coupled with prolonged product shelf life and clearer consumer information on food safety, substantially reduces post-purchase waste. The integration of Blockchain-driven traceability heightens food transparency and nurtures a culture of accountability, motivating all participants in the food supply chain to make responsible decisions consistently. This heightened accountability empowers stakeholders to take increased responsibility for ensuring food safety [109].

Blockchain technology can potentially revolutionize food waste management by offering a comprehensive solution throughout the entire food supply chain. From monitoring initial food production to the consumption phase, Blockchain can effectively reduce food waste, prevent fraud, and address unethical practices that can lead to food rejection or waste. The key to its success lies in leveraging Blockchain's transparency to enhance visibility in food supply chains, safeguarding against wastage and malpractices. This transparency also empowers consumers with detailed insights into the entire food development and delivery lifecycle, enabling them to make informed and environmentally conscious choices. As stakeholders recognize its potential to address critical issues in the food industry, integrating Blockchain technology is expected to become a standard practice, fostering a more sustainable and ethical approach to food production and consumption (Figure 12).

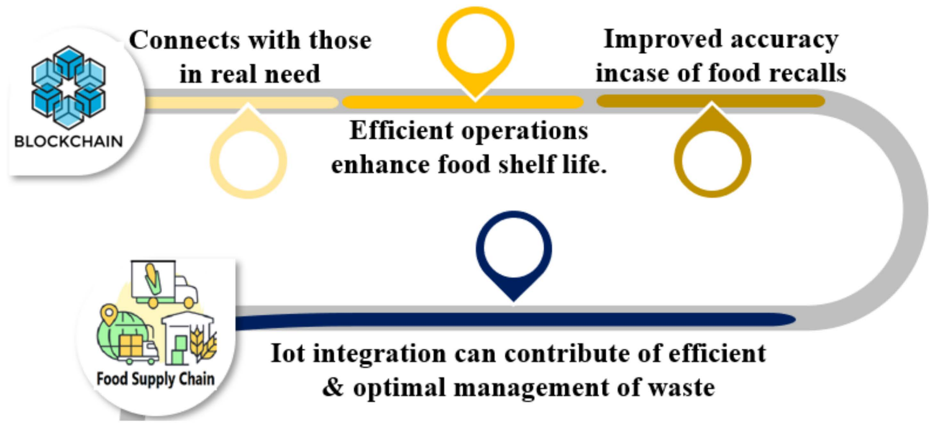

Figure 12. Blockchain application in food supply chains (food waste).

- **Data analysis**

As highlighted by Kamble et al. [110]. Data within an agrifood supply chain are gathered from all four critical processes: planning, sourcing, manufacturing, and delivery. Notably, the planning and delivery stages significantly contribute to enhancing data analytics capabilities, surpassing the impact of the sourcing and manufacturing processes. Due to the variety of stakeholders and processes, the agri-food supply chain comprises various sources for information collection and analysis of data.

Bhat et al. [111] emphasized the challenges in agriculture, including fluctuating market prices, soil degradation, unsustainable crop practices, and the impact of weeds, pests, and global warming. The authors proposed that big data analytics can significantly address these issues within the food and agriculture supply. Big data can provide insights into potential hazards and optimize decision-making by examining diverse data points such as food quality, storage conditions, weather patterns, soil quality, marketing, and trade management. The authors highlighted the importance of considering multiple variables, such as climate conditions and market values. They stressed that a holistic approach involving various technologies, such as big data sharing, Blockchain and cloud storage and data from different sectors are essential to harness the full potential of agricultural big data. They highlighted that research scientists, lawmakers, agriculturists, and vested parties could leverage these data for researching new facts, designing specific policies, making effective decisions, and better managing the food supply chain. For example, Blockchain technology will enable stakeholders to review details relating to product origin, quality checks, transportation, and specific traceability or quality issues (e.g., monitoring temperature or microbial content). This eventually provides the required transparency and reliability in accessing critical data related to products [2].

Advanced computer tools like ANN, PROLOG, and TOMRA's Deep learning technology, use machine learning for analyzing big data and are employed in the processing stage. These tools help extract important information about soil quality, such as nutrient levels and pH. They also analyze seed features, sort food, study weather patterns, and identify potential food hazards. This is carried out by connecting biological or environmental data with the development and likelihood of harmful pathogens, pests, and toxins. Thus, this information can be utilized to boost decision-making procedures [112]. According to Kayikci et al. [113] and Bhat et al. [112], advanced analytics methods such as artificial intelligence and predictive modeling can be utilized to improve supply chain procedures, inventory management, demand projecting, and process improvements leading stakeholders to make more efficient and educated decisions, ultimately reaching far better efficiency.

Integrating cloud technology, artificial intelligence, and data analysis, coupled with Blockchain, enables data-driven farm management practices. This integrated approach encourages farmers to optimize input planning, reduce waste, and improve investment returns. Companies can leverage big data analytics and machine learning (ML) techniques to transform into data factories, developing the necessary skills, attitudes, and technologies [114]. ML-based decision support systems can be applied at the edges and data servers to efficiently process collected data [115]. Manufacturers and distributors benefit from big data analysis and advanced predictive methodologies, incorporating factors such as weather, special events, and evolving marketing trends, enabling them to make timely decisions and improve the estimation of consumer demand [101] (Figure 13).

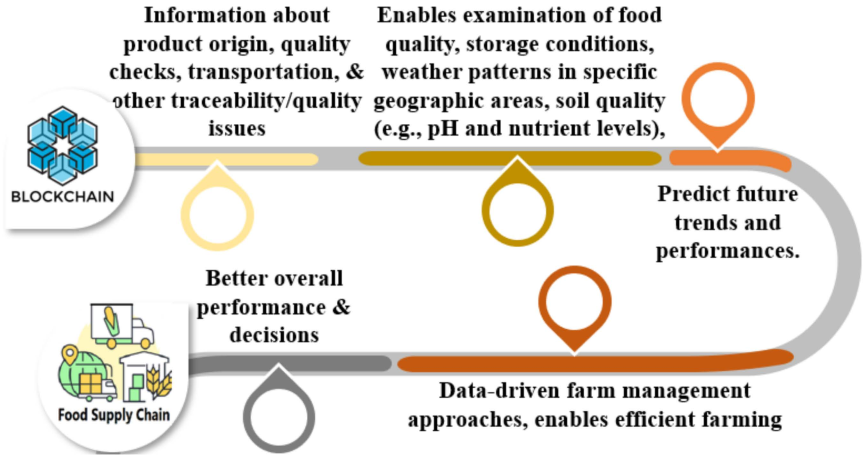

Figure 13. Blockchain application in food supply chains (data analysis).

6. A Framework for Blockchain-Driven Food Supply Chain

The proposed Blockchain-driven food supply chain framework provides a comprehensive, Blockchain-based solution that addresses critical challenges in the food supply chain. In order to create a more applicable and understandable framework, the 12 drivers are further grouped into four categories A, B, C, and D (Figure 14), as follows:

A. Data Integrity and Trust;
B. Operational Efficiency;
C. Sustainability and Safety;
D. Social Sustainability and Safety Management.

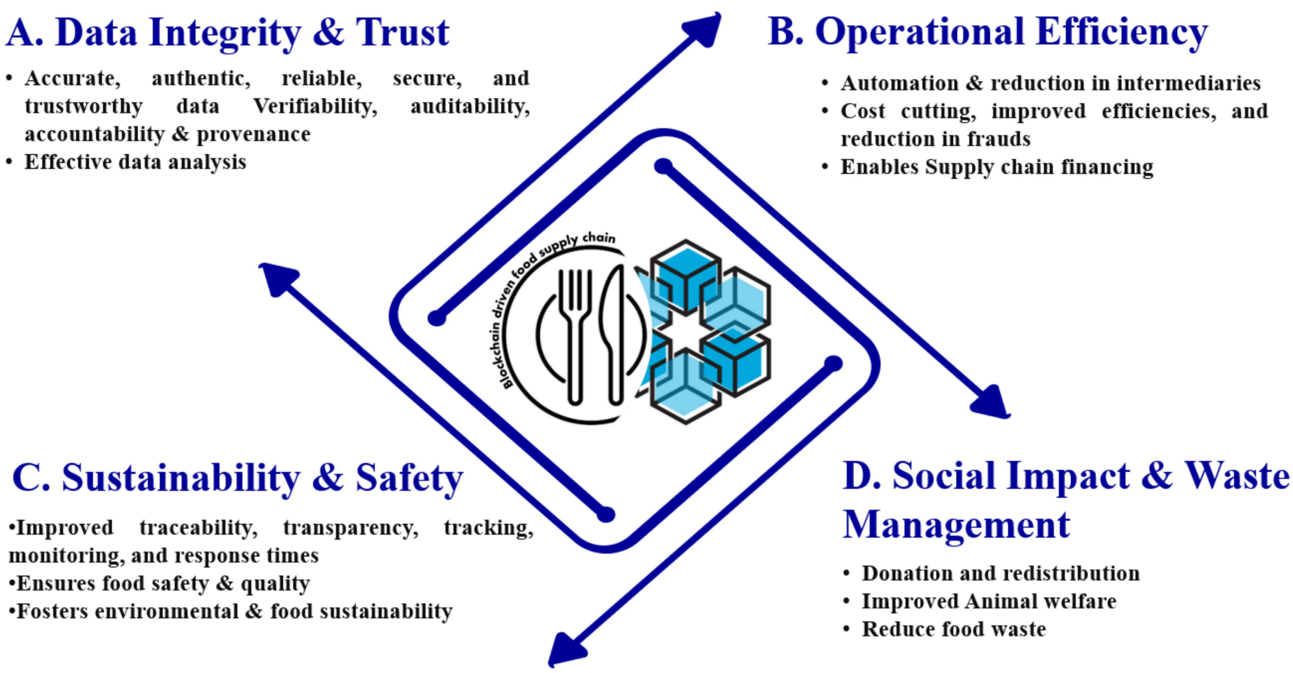

Figure 14. A framework of Blockchain-driven food supply chains.

6.1. A. Data Integrity and Trust in the Food Supply Chain

6.1.1. Accurate, Authentic, Reliable, Secure, and Trustworthy Data

- **Context**: The food supply chain involves multiple stakeholders, including farmers, processors, distributors, retailers, and consumers. Ensuring data integrity at every stage is vital to prevent fraud, mislabeling, and safety issues. Blockchain's immutable ledger provides a permanent, tamper-proof record of each transaction and movement of goods.
- **Impact**: This guarantees that information on the origin, quality, and safety of food products is accurate and reliable, enhancing consumer trust and compliance with regulatory standards.

6.1.2. Verifiability, Auditability, Accountability, and Provenance

- **Context**: In the food supply chain, tracking the origin and journey of food products is crucial for maintaining food safety and quality. Blockchain technology enables a verifiable chain of custody, allowing participants to trace every transaction and change in ownership or handling.
- **Impact**: This transparency ensures that food provenance is indisputable, giving consumers confidence in the products they purchase and allowing businesses to quickly trace and resolve issues such as contamination or mislabeling.

6.1.3. Data Analysis

- **Context**: Real-time data collected from every step in the supply chain provide actionable insights that help optimize processes and improve decision-making. For instance, data on product movement can help identify bottlenecks or inefficiencies in the distribution process.
- **Impact**: Enhanced data analysis leads to better demand forecasting, inventory management, and resource allocation, ultimately reducing waste and improving supply chain performance.

6.2. B. Operational Efficiency in the Food Supply Chain

6.2.1. Automation and Reduction in Intermediaries

- **Context**: The food supply chain often involves numerous intermediaries, such as brokers and third-party auditors, which can slow down transactions and increase costs. Blockchain, through smart contracts, automates these processes by executing predefined agreements without manual intervention.
- **Impact**: This automation speeds up transactions, reduces administrative costs, and eliminates the need for intermediaries, allowing food products to move more quickly from farm to table.

6.2.2. Cost Cutting, Improved Efficiencies, and Reduction in Fraud

- **Context**: Fraud in the food supply chain, such as counterfeit products or false labeling, can harm consumer trust and result in financial losses. Blockchain's transparent and traceable nature minimizes the risk of fraud, while also reducing redundancies in record-keeping and auditing.
- **Impact**: Lowering the cost of operations and reducing fraud leads to increased profitability for producers and more consistent product quality for consumers.

6.2.3. Supply Chain Financing

- **Context**: Small and medium-sized food producers often face challenges in securing financing due to the lack of transparency in traditional supply chains. With Blockchain, verified transactions serve as proof of business activities, which can be used as collateral for securing loans or credit.

- **Impact**: Improved access to financing helps producers and suppliers manage cash flow more effectively, enabling them to grow their businesses and invest in sustainable practices.

6.3. C. Sustainability and Safety in the Food Supply Chain

6.3.1. Improved Traceability, Transparency, Tracking, Monitoring, and Response Times

- **Context**: Traceability is critical in the food supply chain for monitoring the movement of goods, ensuring that perishable products are stored and transported under proper conditions, and quickly identifying sources of contamination. Blockchain provides real-time tracking and monitoring, making it easier to manage recalls and address food safety concerns.
- **Impact**: Faster response times to safety issues or contamination events protect consumers and help companies avoid costly product recalls or reputational damage.

6.3.2. Food Safety and Quality

- **Context**: Ensuring food safety is a top priority in the supply chain, particularly for perishable and high-risk products such as meat, seafood, and dairy. Blockchain technology can monitor key variables such as temperature, humidity, and handling conditions, ensuring that safety standards are maintained.
- **Impact**: By tracking the conditions under which food is stored and transported, a Blockchain helps prevent spoilage, contamination, and foodborne illnesses, ensuring that only safe, high-quality products reach consumers.

6.3.3. Environmental and FOOD Sustainability

- **Context**: Sustainability is increasingly important in the food industry, as consumers demand more environmentally responsible sourcing practices. Blockchain technology can track the environmental impact of production processes, including carbon footprints, water usage, and resource management.
- **Impact**: This promotes transparency and accountability, allowing stakeholders to make informed decisions that minimize environmental harm and support long-term sustainability goals.

6.4. D. Social Impact and Waste Management in the Food Supply Chain

6.4.1. Donation and Redistribution

- **Context**: Food waste is a major issue in the global food supply chain. A Blockchain can track expiration dates, surplus inventory, and locations of excess food, facilitating the redistribution of food to charities and food banks before it spoils.
- **Impact**: By ensuring that surplus food is properly managed and redistributed, a Blockchain helps reduce food waste and ensures that food is used to feed those in need rather than ending up in landfills.

6.4.2. Improved Animal Welfare

- **Context**: Animal welfare is a growing concern for consumers, who want assurances that livestock are raised and handled humanely. A Blockchain enables the tracking of animal conditions, ensuring compliance with welfare standards throughout the supply chain.
- **Impact**: With transparent data on the conditions in which animals are raised, businesses can demonstrate their commitment to ethical practices, and consumers can make more informed choices about the products they purchase.

6.4.3. Food Waste

- **Context**: One of the major inefficiencies in the food supply chain is the amount of food that goes to waste due to poor inventory management, inadequate tracking, or delays in distribution. Blockchain technology optimizes inventory and transportation management, reducing the likelihood of food being spoiled or discarded.

- **Impact**: By improving efficiency and reducing waste, Blockchain technology helps the food supply chain become more sustainable, reduces costs for businesses, and ensures that more food reaches consumers.

7. Limitations

One limitation of this study is that the scope was constrained by the inclusion criteria, which may have excluded certain emerging or niche applications of Blockchain technology within the food supply chain. Additionally, the review only covered studies and frameworks available up to a specific date, potentially missing out on the most recent innovations and advancements in Blockchain applications. Furthermore, the study did not explicitly address geographical variations, meaning that regional differences and specific local challenges related to Blockchain adoption in food supply chains may not have been fully captured in the analysis. These factors could limit the generalizability of the findings across different contexts and regions.

8. Future Directions

Future research should explore the untapped potential of Blockchain technology in areas identified as underutilized, such as food donation and redistribution, supply chain financing, animal welfare, food waste, and food data analysis. Expanding the geographical scope of future studies would allow for a more comprehensive understanding of how regional differences affect Blockchain adoption and implementation in diverse food supply chains. Moreover, incorporating the latest advancements and frameworks that emerged after the cut-off date of this review could reveal new applications and trends in the field. Longitudinal studies that track the real-world impact of Blockchain in food supply chains over time, combined with qualitative approaches, could further enrich the understanding of its efficacy and address context-specific challenges. Additionally, interdisciplinary collaboration involving stakeholders from agriculture, technology, and policymaking will be crucial in fostering a holistic development of Blockchain-driven food supply chains.

9. Conclusions

The findings of this research highlight the considerable function of Blockchain technology in enhancing food traceability and supply chain administration, as shown by its effective implementation in numerous studies. By incorporating Blockchain innovation, different stages of the food supply chain can be improved, thus introducing a detailed and holistic picture of Blockchain-driven supply chain. Nonetheless, there are still areas within the food supply chain that have not been leveraged by Blockchain. The research further highlights that ensuring surplus food distribution and reducing food wastage is a significant reason for the importance of food donation and redistribution models grounded in Blockchain technology. Additionally, the availability of a transparent accountability system through Blockchain will efficiently track and dispose of waste thus enabling better resource management throughout the food supply chain. Furthermore, enhancing supply chain finance with Blockchain technology will lead to improved risk management, trust, and security among participants in the food supply chain. This, in turn, streamlines operations and contributes to reducing the days of the food cycle. Following our research goals, a framework is presented to depict an extensive and detailed understanding of the food supply chain driven by Blockchain technology.

The integration of Blockchain technology in the food supply chain achieves significant improvements across four key areas: Data Integrity and Trust, Operational Efficiency, Sustainability and Safety, and Social Impact and Waste Management. By ensuring tamper-proof, transparent data, Blockchain fosters trust and accountability at every stage. It streamlines operations by automating processes and reducing intermediaries, improving efficiency while cutting costs. Blockchain also enhances sustainability by tracking environmental impacts and ensuring food safety through real-time monitoring. Additionally, it addresses social challenges by reducing food waste, redistributing surplus food, and ensuring ethical animal welfare practices, creating a more transparent, efficient, and sustainable food system. Additionally, the proposed framework is more holistic than previous models as it not only addresses core aspects like data integrity, efficiency, and safety but also incorporates social impact factors such as food redistribution, waste reduction, and animal welfare, creating a comprehensive solution that balances operational performance with ethical and sustainability goals throughout the food supply chain. This research not only improves our existing understanding of Blockchain's influence but also works as a foundation for future study, urging stakeholders and scientists to explore and maximize the untapped possibilities of Blockchain technology in the food supply chain.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/app14198944/s1, Annexure S1: Total count of food-traceability and supply chain systems based on Blockchain that were methodically examined.

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