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Achieving UN SDGs in Food Supply Chain Using Blockchain Technology

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Abstract: Food supply chains are highly distributed, collaborative, heterogeneous, diverse, and varied by product, process, and destination. The global food supply chain (FSC) objective is to maintain a good balance between supply and demand and move products from producer to market. However, sustainability of the FSC has become a major concern as limited resources and increasing population pressure threaten its existence. Supply chain management is an important issue for FSC due to information flow throughout the supply chain. Industry-specific characteristics and extensive integration among multiple actors in an entire supply chain exacerbate this situation. The agri-food sector has one of the lowest rates of information technology penetration for innovation. Over the past thirty years, information and communication technology (ICT) has been introduced into the agricultural and food sectors, helping to improve food production and transportation. However, there are various challenges, such as transparency, accountability, food scandal, trust, and inefficient information flow, that the food supply chain is still facing in reaching sustainable goals. The complexity of food supply systems and the opportunities and challenges faced regarding desired sustainability performance need to be examined to achieve the United Nations Sustainable Development Goals (SDGs). Blockchain is an emerging and disruptive digital technology that can transform governance and sustainability in integrated food supply chains. It provides a transparent, immutable, and traceable ledger that minimizes anomalies and information fraud, making it a potential solution for designing a transparent, traceable food system. Blockchain can potentially improve the sustainability of the food supply chain by providing a transparent traceability system. Food traceability is important for managing the food supply chain and protecting public health. It allows quick and accurate traceability of contaminated food that causes foodborne illness outbreaks, leading to the withdrawal of contaminated food from markets. Blockchain can achieve traceability, provenance tracking, transparency, and reduce environmental impact in the food supply chain. It also helps in achieving sustainable development goals set by the UN. However, there is no scientific research on blockchain's contribution to achieving these goals in the food supply chain. Therefore, this article presents a systematic literature review and thematic analysis to study the relationship between FSC sustainability, blockchain, and sustainable development goals.

Keywords: blockchain; food supply chain sustainability; food fraud; food security; food safety; smart contract; systematic literature review; SDGs; traceability; transparency

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1. Introduction

The food supply chain (FSC) plays a significant role in meeting food and nutritional needs. The FSC is a complex global system with highly diversified production, processing, and transportation infrastructure. It is highly distributed, cooperative, heterogeneous, and diverse and varies according to products, production processes, and destinations.

FSC management aims to balance demand and supply by transporting produce from the producer to the market. However, the sustainability of the FSC is becoming a major concern, given finite resources and increasing population pressures. Sustainability depends on several factors, including food shelf life, spoilage rates, transportation distance, and costs associated with production processes along with transportation costs.

The Food and Agriculture Organization published a report, "*The future of food and agriculture: trends and challenges*" [1], highlighting different FSC challenges, including poverty and inequality, hunger and malnutrition, sustainable production, and national and international governance. Other challenges include food quality, food safety, food security [2], environmental sustainability, demand–supply gaps, and the unavailability of information [3]. These challenges are interlinked with the UN Sustainable Development Goals 2030 (SDGs 2030), which defines seventeen specific Sustainable Development Goals (SDGs) along with 232 sustainability indicators. The SDGs are a broader perspective for achieving sustainability across various domains of human life at a country level. However, SDGs such as No poverty (SDG-1), Zero hunger (SDG-2), Good health and wellbeing (SDG-3), Clean water and sanitization (SDG-6), Sustainable production and consumption (SDG-12), Climate action (SDG-13), Life below water (SDG-14), and Life on land (SDG-15) have a direct relationship with food supply chain sustainability. Other SDGs are related indirectly because all SDGs are explicitly interdependent [4].

Presently, food security is a key challenge that the world is facing. It is described as "A situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" [5]. According to this, availability, accessibility, utilization, and system stability are the four main dimensions of food security. The demand for food is growing faster than population growth due to changing living styles and food habits, posing challenges to meeting food security requirements [6]. Demand for high-quality, nutritious food from animal products must be addressed sustainably by minimizing environmental impact and social prospects. In this respect, investment in technologies and innovation is vital, specifically in low and middle-income nations with a higher population growth rate. It is highly unlikely that the current investment structure in the agricultural sector will deliver a sustainable solution in a rapidly changing world. "Future of Food: Trends and Challenges", a report published by the Food and Agriculture Organization, identified the need for an adequate and affordable food supply through agricultural services to meet the growing needs of an increasing population. The agriculture and food sector also greatly impacts economic gains and jobs, contributing to 5.9% of global gross domestic product and at least 35% to global employment [1].

One of FSC's key challenges is managing information exchange among supply chain stakeholders. Industry-specific characteristics and the heterogeneous nature of stakeholders exacerbate this situation. A cautious need-to-know attitude to most "one up, one down" information flows systems is a challenge; for example, farmers can exchange information with processors and wholesalers but cannot do it directly with retailers. This cautious approach becomes a deeper problem in complex supply chains for processed or packaged foods. Lack of information has long been recognized as an important issue in agribusiness that affects the overall efficiency of the supply chain [7]. As consumer demand for sustainable food products grows, the pressure on the industry becomes greater. To meet this demand, more transparency is needed in the face of pressure from consumers wanting to know more about food provenance and the production process in the context of health and safety and its environmental impact. A transparent traceability system improves the ability to respond to food emergencies. However, achieving these desired outcomes is challenging due to the complexity of food production and processing, the diversity of culturally diverse SMEs (small- and medium-sized enterprises), and the lack of appropriate institutional infrastructure. Although the agri-food sector is a large commercial and industrial sector, it has one of the lowest innovation and information technology penetration rates. Over the past thirty years, ICT has integrated into the agricultural and food sectors to improve production, transportation, and efficient management of the food supply chain. However, adopting these solutions has been slow for several reasons, including a lack of knowledge, high investment requirements, and the expertise needed to implement them. Another factor leading to the slow adoption of ICT is that existing solutions—such as logistics services and farm information management systems—are closed proprietary systems. The scaling capabilities of these systems are commensurate with their cost, and interoperability between them is challenging to ensure supply chain transparency.

Agricultural and food supply systems are complex and require attention to achieve sustainability. Climate change has the biggest impact on food supply chain sustainability. Still, other critical issues related to sustainability include shifts in agriculture financing, changes in food systems, food security governance, changes in eating patterns, and nutritional demands. Blockchain is an emerging and disruptive technology that can change food supply chain sustainability and governance. A systematic literature review on blockchain's theoretical and exploratory implementation across various aspects of the food supply chain sustainability was presented. A relational framework was created to show the dependency between sustainability, blockchain, and SDGs.

The rest of the paper is organized as follows: Section 2 provides a brief overview of blockchain technology. Section 3 outlines the challenges in food supply chain sustainability. Section 4 describes the methodology used in this research. Section 5 presents a thematic analysis of the reviewed article and relational framework, and Section 6 discusses future directions and conclusions.

2. Blockchain

The blockchain is a distributed ledger that stores data in an immutable form using a hashing algorithm and consensus mechanism. The blockchain enables a transparent, distributed data storage system where node-to-node transactions occur. Blockchain can be seen as a combination of digital technologies comprising distributed networks, consensus mechanisms, hashing algorithms, public–private key infrastructure, and cryptography. Blockchain's first-generation use case was in digital currency creation and transaction, where it was used to store transactions of digital coins (cryptocurrencies) independent of a centralized authority such as centralized banks. It is followed by the second-generation blockchain, which includes smart contracts that support automation and fundamental building blocks of decentralized applications and provides more functionalities, commonly referred to as Blockchain 2.0 [8].

Smart contracts unlock blockchain potential across several sectors, such as the supply chain, health care, information management, voting, insurance, and identity management. A smart contract is "a set of promises, specified in digital form, including protocols within which the parties perform on these promises" [9]. Blockchain ensures that all participants in the shared ledger witness all promises and actions, making it difficult, if not impossible, to circumvent or reverse actions taken after that. Blockchain is characterized by decentralized, asymmetric cryptography, time stamp, trustless, and smart contracts. Blockchain helps build mutual trust and confidence among businesses that partner without a central authority, ensuring transparency through consensus protocol.

Blockchain can be compared to a database like a ledger, where digital data are stored on a ledger page, and each page of the ledger is hashed and then digitally connected with the next page. One major difference with a blockchain database is that data, once stored on the blockchain, cannot be changed or altered, or deleted. It remains there forever. Data stored on blockchains can include simple transaction data and computer programs known as smart contracts. These smart contracts automate business logic by receiving information from outside sources; these input data can be fetched from the blockchain or entered from outside using an oracle, whereas the output is stored on the blockchain. Smart contracts build distributed applications that bring more transparency and automation to business processes. The immutability of blockchains supports smart contracts as a trust-building block among business partners because they cannot be modified once executed.

3. Food Supply Chain Sustainability Challenges

Sustainable food systems can be achieved through environmentally and socially centered economic solutions to fulfil current and future populations' food and nutrition demands. The three fundamental challenges that must be managed collectively to obtain optimal trade-offs include feeding a fast-growing population, providing livelihoods, and protecting the environment [1]. These challenges can be improved with better policy design and implementation. Policy design is one of the greatest challenges in achieving the SDGs. The policy design process involves many factors, including competition in the industry and rapid rationalization, supply chain integration, food safety and quality concerns, potential environmental impact, changing consumer preferences for healthier meals, changing labor demands, and biosecurity risks [2,10].

The global food supply chain is expected to meet the demand for food for an estimated population of 8.5 billion by 2030. It is an increase from today's 7.6 billion people, which has grown steadily since 2000 [11]. Food insecurity is a major challenge; it is understood that food production is increasing, but demand is increasing more rapidly. Food production and wastage are also growing rapidly with a rise in overall demand, increasing income, and lifestyle. These factors contribute to climate change and food security, two major concerns moving forward to achieve the UN Sustainable Development Goals (SDGs). Agriculture and food production employs a labor population and financially support people to contribute to the "No Poverty" goal—specifically in developing and underdeveloped countries. The global food supply chain, along with modern intensive farming, involves many farms' machinery and significant transportation of food from production sites to consumption sites, contributing significantly to GHG emissions and climate change. Overall, farming is one of the prime contributors to global GHG emissions [12].

The primary drivers behind poor sustainability practices in the food supply chain are a lack of government policy, technology, knowledge, and awareness among farmers [13]. Educating farmers about sustainability practices and training them to use the latest modern technology will be key to achieving food sustainability. However, it will be a slow process and may take a generation before substantial results are delivered.

Food safety is also important in achieving the UN's zero-hunger goal. Recent food safety scandals involving baby milk powder, horse meat, and *E. coli* bacteria have put many people at risk of foodborne illness [14–16]. Several latest technologies are being used to prevent and improve food safety incidents, such as RFID (Radio Frequency Identification), Internet of Things (IoT), and machine learning (ML) [17]. These technologies and algorithms can be used to access and analyze raw material procurement, logistics, processing, warehousing, and distribution data to design a traceability system that helps detect and track food safety issues. However, these technologies have their drawbacks, such as low transparency, data privacy, and centralized data storage, which potentially cause information loss and data tampering [18].

The food supply chain is a centralized system with several issues linked with integrity, trust, transparency, traceability, and transaction. There is a lack of trust, transaction delay and fraud, and tracking irregularities among supply chain partners. Traceability and transparency are prime factors that impact food supply chain sustainability. More than 400 sustainability standards are vying for the attention of adopters and consumers. While all standards are based on the three pillars of sustainability (economic, social and environmental), they were given a different weightage in creating a standard. The four most employed standards (Rainforest Alliance Certified, Fairtrade, Organic/Bio, UTZ Certified) differ in scope and purpose [19]. These various sustainability initiatives compete to determine what criteria a standard must meet to promote sustainability effectively. This can lead to a lack of safety and trust in these initiatives among professionals and consumers. There is a need for cooperation between different sustainability standards. In this aspect, agreeing on a particular standard is less important than implementing a transparent and independent standard. These independent indicators' standards should be regularly tested and certified by an independent organization. Certification is equally important as standard awareness, which requires considerable effort from all supply chain stakeholders to ensure sustainability with producers [10].

The United Nations presented 17 Sustainable Development Goals (SDGs) to achieve sustainable practices across all sectors at the national level. Integrating FSC sustainability practices into the SDGs enables the development of sophisticated and advanced supply chain management strategies that can lead to more stable, ethical and efficient food supply chains. Although the SDGs represent a different approach to sustainability assessment, their potential to transform mainstream governance approaches to food supply chain sustainability remains open for discussion and research. The global community's decision to evaluate and practice sustainability is taken collectively and encourages each nation to implement it. These decisions are executed under different circumstances and introduce new practices that yield new ideas and actions for sustainability [20]. However, developing an integrated food supply chain sustainability management aligned with SDGs is a complex process. Management planners may encounter numerous obstacles and limitations in implementing sustainability assessment objectives. It needs the involvement of all supply chain partners to integrate SDGs and the food supply chain for sustainability practices to be successful.

It should be noted that not all SDGs contribute directly to food supply chain sustainability. No research that discusses FSC sustainability alignment with the SDGs and the use of blockchain technology is available. Those SDGs that are observed to be directly related to the FSC include No poverty (SDG-1), Zero hunger (SDG-2), Good health and wellbeing (SGD-3), Responsible consumption and production (SDG-12), Climate action (SDG-13), Life below water (SDG-14), and Life on land (SDG-15).

4. Research Method

This article adopted a systematic literature review (SLR) methodology to identify, select, and critically evaluate the research article [21] to identify the blockchain application in food supply chain to address different SDGs. SLR methodology comprises four stages: define research questions, literature collection, exclusion and inclusion criteria, and material evaluation.

4.1. Research Questions

Research question and objective of this research was presented in Table 1.

Table 1. Research question and objective.

#	Research Question	Research Objective
RQ 1	To identify food supply chain sustainability challenges in line with UN SDGs?	This research question investigates FSC sustainability challenges and aligns them with the SDGs.
RQ 2	What features of blockchain are being used in literature to solve the sustainability challenges identified in RQ 1?	The primary objective is to explore how blockchain was used in literature to solve sustainability challenges of the food supply chain to achieve SDGs.
RQ 3	How can blockchain be used in achieving the SDG?	The primary objective was to uncover the interaction among identified FSC challenges, blockchain applications and SDG.

4.2. Material Collection

A systematic literature review's first step is to collect relevant literature. The documents included for the analysis include peer-reviewed articles, conference papers, theses, and dissertations. Documents were searched in scientific databases Scopus and Web of Science published between January 2009 to July 2022. In search criteria, 2009 was used as important filter criterion because first application of blockchain technology emerged in 2009, in the form of Bitcoin [22]. However, its application in food supply chain sustainability was first published in 2016 [23]. Therefore, articles that were reviewed and analyzed in this research were published between 2016 and 2022 (Figure 1). The search keywords to select relevant paper was constructed based on objective of this research. The search terms used for search in the database were "blockchain*" or "distributed ledger" and "food supply chain", or "agriculture supply chain", or "food supply chain sustainability", or "agriculture supply chain sustainability".

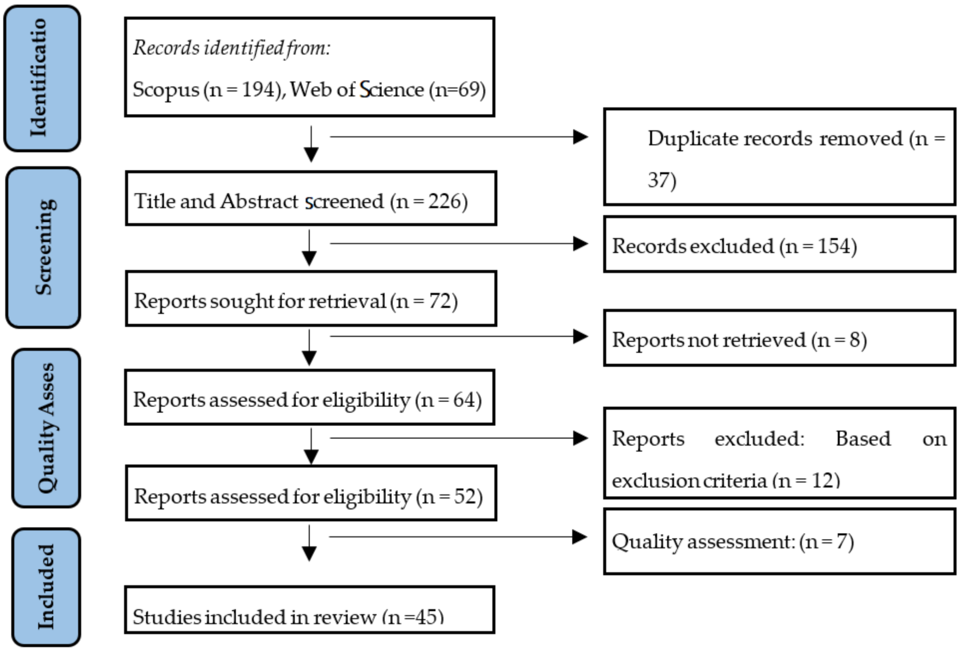

Figure 1. Systematic literature review.

4.3. Exclusion and Inclusion Criteria

The articles that sparsely mentioned blockchain and supply chains without any sustainability issues were excluded. There were other instances where articles had both terms, but overall, the articles did not contribute to this field. Few articles mentioned the concept of blockchain and the food supply chain. However, no solution or analysis was presented to address the research questions. Another exclusion criterion was the language of the article.

4.4. Descriptive Analysis

This study analyzed 45 research articles published between 2016 and 2022, which include blockchain applications in the food supply chains for various objectives such as traceability, transparency, monitoring, food safety, provenance, and governance which contribute to enhancing the sustainability of food supply chain. Even though blockchain is a concept that started a decade ago, its application in the food supply chain sustainability is in early stages. Therefore, limited literature is available in this domain. However, research interest has rapidly increased in the last couple of years. A thematic analysis was selected to categorize selected articles based on themes. The primary theme was food safety and quality, food insecurity environmental sustainability, and food trade and policy.

4.5. Category Selection

This stage involved categorizing collected literature according to the research problem and objective. All the selected articles were classified into six categories: problem statement, proposed solution, methodology, data set, application area, and findings. These categories are effective in the structural analysis of each article to identify the research contribution. Moreover, analysis of the sub-categories within problem and solution categories, e.g., in the problem category, different issues were summarized, such as food security, food safety, traceability, cost, performance, infrastructure, and food quality.

5. Blockchain Adoption in the Food Supply Chain to Achieve SDGs

Innovations in information and digital technology are changing how industries and consumers communicate, interact, and share information. These innovations come from smartphones, smartwatches, drones, Internet of Things (IoT) computers, artificial intelligence, and machine learning. These innovative devices and algorithms benefit the food supply chain in various ways. For example, monitoring climate change and analyzing its impact on the food sector [24]. Information and communication technology benefits the global food supply chain by offering real-time critical data, analysis, and digital technologies during pre-harvest and post-harvest operations. It can also be used to develop traceability systems that track food production and transportation processes from farm to fork.

Blockchain technology is not only seen as a tool that enables transparent and reliable transactions within the food supply chain but also contributes to reducing transaction costs, supply chain governance, and resource functions. Blockchain applications in food supply blockchain adds value to trust, security, traceability, and decentralization. Blockchain-centric food supply chains create information symmetry using blockchain as a data structure. The food supply chain stakeholders can store and exchange information confidentially and transparently, use smart contracts, and execute various supply chain activities such as automated payments to vendors. A smart contract can also replace traditional legal and financial contracts.

Blockchain technology is also a strategic tool that can impact supply chain restructuring and food companies' capabilities. More specifically, investments for blockchain implementation along the supply chain led to increased bilateral dependence between supply chain partners and a higher degree of coordination of vertical relationships. It will also contribute to the advancement of stable relationships and improved collaboration among supply chain partners. In addition, adopting blockchain will develop competencies that help manage innovation along the chain and other competencies that give a competitive advantage [25].

Blockchain, combined with other technology such as sensors, IoT, cloud, and artificial intelligence (AI), enables real-time data access and brings accountability and transparency to the food supply chain. Blockchain combined with IoT can impact areas such as provenance, payments automation, quality check, and management of the food supply chain [26]. Additionally, processing and analyzing a large dataset from the blockchain and AI application provide a better understanding and insight into the supply chain that will help move towards sustainable food production and consumption cycle. Blockchain application in FSC provides a transparent and reliable traceability system which is important in protecting public health because it can quickly and accurately track the source of contaminated food, fruit, or vegetables suspected to be responsible for developing foodborne diseases.

Among the 17 SDGs of the UN, the Food and Agriculture Organization is custodian 7 SDGs, including "Zero hunger (SDG-1), Gender Equality (SDG-5), Clean Water and Sanitation (SDG-6), Responsible consumption and production (SDG-12), Climate action (SDG-13), Life below water (SDG-14) and Life on land (SDG-15)". Therefore, these indicators are directly linked to the food sector. Blockchain applications in FSC could help achieve SDGs in improving food safety, transparency, traceable inventory management, auditing, regulation and supervision, fraud detection, scalability, data security, and reduced costs [27]. This paper will discuss various aspects of the blockchain feature and its application in FSC that could lead to achieving SDGs.

5.1. Food Safety and Quality

Over the last few decades, numerous food scandals and mislabeled food information have brought great attention to food safety issues and heightened consumer concerns about food quality, such as mad cow diseases, horsemeat scandal, melamine baby milk formula, and many more [15,28]. The Food and Agriculture Organization describes food safety as "absence (or acceptable levels) of food hazards that may harm consumers' health." Food can easily be contaminated during processing, packaging, transporting, and storage. Therefore, food safety must be guaranteed during all these steps in the supply chain. Food safety is a critical global food supply chain issue and falls under the Zero hunger (SDG-2) goal, whereas food quality directly influences the health of people (SDG-3) (Figure 2). The food supply chain is a complex system spread across the globe. Therefore, collecting food safety data and its verification to provide transparent traceability is difficult. A complete food tracing system from production to retail is essential for protecting food quality and safety.

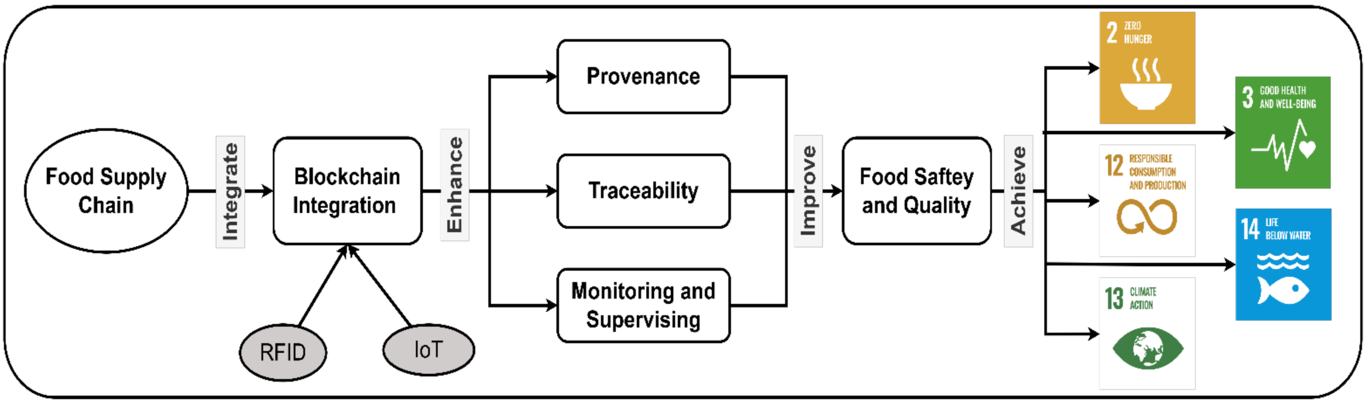

Figure 2. Food safety and quality and SDG.

While food safety is a key concern for customer wellbeing, the participation of producers is also essential in a formalized global supply chain to increase income and reduce market uncertainty. It is important to adopt a transparent process to certify ethically and sustainably produced food products [29]. Transparency will increase the perceived value of healthy and safe foods and consumer willingness to pay for them. Ensuring food safety, quality, traceability, and post-harvest management is a complex and intricate issue in the food supply chain. With the advancement of digital technology and social media, consumers are more concerned about their food choices. Agri-food producers are well informed about consumers' demands for healthy products made with natural ingredients and non-adulterated processes. Assuming that consumers read product labels attentively to get informed about product sustainability, blockchain can become an important tool to monitor and provide a transparent label that consumers can trust. It will also force producers to offer higher-quality products [30]. Digitizing the food supply chain and adding other technology along with blockchains, such as Radio Frequency Identification (RFID) and IoT, can reduce the potential for error and fraud and improve transparency and product traceability [17,31].

5.1.1. Food Traceability

Food traceability is important for food safety. Traceability helps in tracking the food product from its origin to consumption. In the case of a food safety issue at the consumer end, traceability can help track the product's origin and find causes for safety issues [32]. The International standard organization (ISO) describes traceability as a "technical tool to assist an organisation to conform with its defined objectives and is applicable when necessary to determine the history, or location of a product or its relevant components" (ISO 22005:2005). Replacing the paper-based tracking system with a digital one means that data from the "farm to fork" tracking system can be accessed in a few seconds.

On the other hand, the food industry could reduce food waste with a digital traceability system and deliver ecological and economic sustainability. The FSC poses many problems, including food fraud, label tampering, excessive use of pesticides and fertilizers, and illegal production, which could be resolved with a transparent traceability system. The lack of food traceability or poor traceability causes serious concerns about food contamination, insecurities, loss of consumer trust, and product recalls. Competition drives the value chain when businesses and global markets are highly efficient. From a marketing standpoint, traceability throughout the supply chain ensures consistent product delivery to customers by ensuring food safety at a high standard. Three requirements must be met to provide end-to-end transparent traceability: (a) verify data source for any data manipulation prior to transmission to maintain data integrity, (b) store data must be immutable and tamper-proof and accessible to the user in a transparent manner, and (c) the confidentiality of the data and the interests of the producer must be protected. Therefore, a basic food traceability system can be modelled to fulfil these three important criteria. However, it is very challenging to develop a concrete traceability model to address concerns about food quality and safety due to large number of food products in the food industry.

Recently, blockchain has been used extensively in designing transparent traceability systems for the food supply chain [33]. The blockchain-based traceability system is characterized by data integrity, security, transparency, reliability, real-time information exchange on hazardous materials, and the ability to trace dynamics. However, a blockchain-based traceability system is insufficient for food safety and quality. Integration of other latest digital technologies, such as the Internet of Things (IoT), RFID, and Artificial Intelligence could offer a better transparent and trustable traceability system. IoT devices automate data-receiving processes without human interference and store them on the blockchain. Minimizing human involvement will enhance food safety [34].

In [35], a blockchain and IoT-based traceability were presented called BRUSCHETTA to track Extra Virgin Olive Oil (EVOO). This platform prevents falsifying data, allowing consumers access to tamper-proof product history and assured product quality. Likewise, in [36], a grain supply chain traceability system was proposed. A smart contract was used to store quality and hazardous-material information and compare it with industry standards. In [37], blockchain was utilized in designing a traceability system for the cocoa bean supply chain. Blockchain has improved the transparency of the cocoa bean traceability system, which improves food safety and information exchange, fulfils consumer demands for safer food, reduces child labor, and stops unethical practices. In [25], blockchain applications showed promising improvement in only the product's external quality attributes, while internal quality remains the same. This could be because the actors in the supply chain agreed on product quality protocols before deploying blockchain.

In the case of perishable goods, monitoring the temperature along the supply chain to ensure food quality is important. Blockchain, along with IoT sensors and QR codes, can be used to guarantee quality and prevent food fraud [38]. For example, in a fish supply chain, IoT and blockchain-based fish tracking systems can be designed to monitor fish quality along the supply chain by recording the fishing location time and continuously monitoring temperature, salinity, and dissolved oxygen during transportation [39]. The QR code can be integrated into the system to enhance system productivity. The QR code provides an easier interface for details such as catch area, fishing date, location, transporter, and transporting condition [40]. It can be further used to analyze and support sustainable marine ecosystem practices and stop excessive fishing in a geographic location [41]. Consumers can access these details to make an informed purchase decision to buy quality and safe produce. The regulatory authorities can also verify the product's compliance with given rules and standards. Blockchain can also be utilized in the distribution of perishable products. It could verify and exchange real-time transparent, tamper-proof warehouse and transportation data to analyze food safety and quality [33].

In [18], blockchain technology, along with visual techniques such as migration maps, heat maps, and directed graphs, was used to visualize an unqualified product, food safety risks, and product tracing in the supply chain. The visual technique supports risk assessments and provides a better management capability to reduce food safety and protect consumer health. In [42], a blockchain-based livestock monitoring system was proposed to trace contamination in production, food authenticity, and disease warning. Similarly, in [43], a blockchain-based traceability system was presented for Australian beef sold in China. The prototype analysis showed that customer trust has improved with a blockchain-based credentialed traceability system.

The management culture applied to the food supply chain impacts the quality of the end product and the vitality of companies. A blockchain-based food supply chain management system that leverages IoT and AI technologies were proposed in [44]. It manages user information, meat product pricing at all levels for each batch, and traceability information on meat products. If the industry publishes enough data from the food supply chain, consumer confidence can be restored in the food industry, which has been damaged due to several food scandals. The visibility provided by the blockchain is scalable to auditors and authorities. The provision of audit data on the blockchain can be facilitated by smart contracts that automate compliance with food safety standards [45]. Companies can utilize the blockchain to maintain product safety records for marketing claims that can be shared with third-party supply chain partners, tax, customs, or certification authorities. Policymakers may also access this data for policy design, financial planning, and legal cause.

5.1.2. Monitoring and Supervising

Government agencies can use the blockchain to achieve multi-faceted management of the food market and safety and quality monitoring. A blockchain-based supply chain where regulatory authorities are a node that can record data on food market transaction information can resolve regulatory challenges in food quality checks [46]. A blockchain-based food supervision system supports transparent and trustable information exchange among supply chain partners, regulators, and consumers. The regulator can verify food safety and store verification data on the blockchain. The blockchain-based system can be designed to protect businesses' data privacy by providing the required data only to the regulator to verify the safety and quality of produce. In [47], a blockchain credit evaluation system was suggested to monitor and supervise trading partners for food supply chains. It collected feedback on produce, traders' behavior, and reliability of the supply chain using a smart contract. This feedback was then analyzed using a deep learning method to determine the credit rating of a trader. A trustable credit information system of the supply chain partner can be used to choose a reliable and trustable partner. The regulator can utilize credit information to penalize and award traders based on their rating, whereas credit ratings help the consumer select better-quality products. The consumer can check food quality and safety data online and can trust these data [48].

In [49], a blockchain architecture called SHEEPDOG was proposed to enable a secure, trustworthy, and privacy-preserving food monitoring system to reduce food scandals. This attribute-based credential mechanism integrated sensors and IoT devices into a blockchain using a public–private key. The data stored on the blockchain were trustworthy and transparent, as they could be verified using the public–private key. Similarly, in [50], a blockchain-based product monitoring system was presented that could integrate with existing infrastructure and store product data across the supply chain. It was employed to trace the livestock from farm to store. RFID was used along with blockchain to streamline product identification. A smart contract algorithm can be designed that compares the national standard targets for food additives and temperature control with the recorded values to automate food quality monitoring and address any safety issues quickly [51].

Mislabeled food products, where misleading information was provided on a product's label to gain economic benefit, cause more significant concern for food safety and consumer health. In [52], an image-based traceability system was presented to counter fake labeled products. In their example, the proposed system and the blockchain provide tamper-proof traceability for honey production. A pollen signature verification using artificial intelligence was used to verify the origin of honey. The traceability of data stored on blockchain by image tracing prevents misleading information and data manipulation.

Similarly, in [53], a physical attribute-based product verification system using machine learning was proposed. The physical attribute of a product includes a visual feature, geographic location and chemical composition. The verification of food fraud can be detected using a machine learning algorithm. However, while the proposed system helps detect fraudulent food products, it requires higher computation power, which is done off-chain. A comprehensive list of literature discussed food security issue respective achievable SDGs was presented in Table 2.

Table 2. Food sustainability issue and SDG.

Food Sustainability Issue	Article	SDGs
Food Safety and Quality	[39–41]	1, 3
Food Traceability	[18,25,35–37,42–45]	
Monitoring and supervising	[49–53]	3, 12, 13
Food Provenance	[25,35,54,55]	1, 3, 12, 13, 14

5.1.3. Food Provenance

The provenance of food products provides information on their origin. Food provenances are essential for ensuring food safety and offering awareness to the consumer about the product's environmental and social impact on local economy. However, tracking provenance is challenging when having numerous supply chain partners physically dispersed throughout a complex food supply chain. The provenance of products can help in achieving the sustainability goals of Zero hunger (SDG-1), Good health and wellbeing (SDG-3), Responsible consumption production (SDG-12), Climate action (SDG-13), and Life below water (SDG-14) (Table 2).

Agricultural provenance systems based on blockchain use decentralization, consensus trust, collective maintenance, and reliable data to solve the trust issue in provenance tracing systems [54]. In [35], a blockchain-based provenance and certification system called BRUSCHETTA was proposed to provide information on the origin of Extra Virgin Olive Oil produced in Italy. The virgin oil produced in Italy has good quality, so it can be understood by knowing its provenance. Likewise, in [55], a blockchain-based provenance tracking system was proposed for the agricultural and food supply chain. It was deployed over Ethereum blockchain network and integrated a reputation system with the blockchain to ensure the credibility of product owners and the assets provided. The blockchain allows end users to see their food before it is consumed. Consumers can see the food's origin and supply chain at the table. In addition, blockchain technology adoption has improved customer satisfaction along the food supply chain and benefited from enhancing vertical relationships and collaboration [25].

5.2. Food Insecurity

Food insecurity, also known as food accessibility, will reduce inequality in food distribution and elevate the living standards of people living in extreme poverty (SDG-1). A good food accessibility system will support the achievement of SDG-2 (Zero hunger) in terms of malnutrition. Food utilization also provides stable incomes in rural economies to improve their quality of life (SDG-1, No Poverty) (Figure 3). One of the targets of the Zero Hunger goal is to end hunger and ensure food access to all by 2030. A nation must have a strong public distribution system (PDS) food program, especially in developing and underdeveloped countries where a large population relies on PDS to achieve zero hunger. PDS plays an important role in improving accessibility of food to vulnerable and poor populations. However, inefficient and non-transparent corrupt PDS make it challenging for the government to reach out to the target population. A blockchain-based public distribution system will bring transparency and reduce corrupt activities. The transparent and decentralized PDS will reduce malicious activities and enable a consumer to know the fair price of goods. Government agencies can also retrieve real-time food stock data from distributors. Tamper-proof data available on the blockchain can be further used for current policy assessment and future policy-making [56]. In [57], a prototype PDS system based on blockchain was presented to distribute food to beneficiaries. This system was designed from procurement to distribution end, which provides real-time stock data to help in reducing wastage at the store. The quality control authority can ensure the quality of food procured and enter quality certification on the blockchain. This decentralized and transparent system ensures that food is distributed impartially and reaches beneficiaries on time. However, this system was not fully transparent due to manual data entry, which resulted in a lack of trust. It can be further improved by integrating IoT and sensors to automate data entry into the blockchain. A combination of blockchain and IoT-based PDS can further reduce malicious actor activities, helping reduce corruption. A blockchain-based system can also audit PDS, ensuring accountability and restoring the consumer's trust [58]. A comprehensive list of literature discussed food security issue respective achievable SDGs was presented in Table 3.

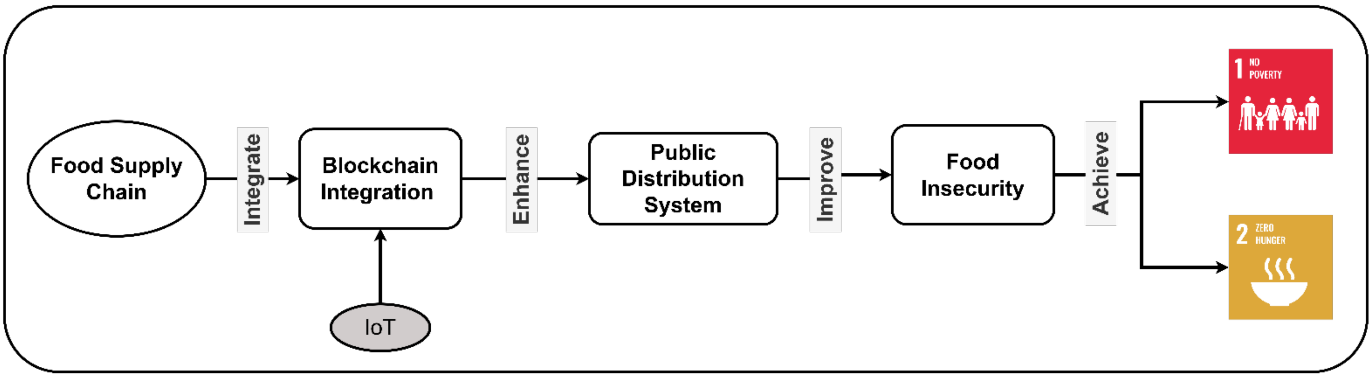

Figure 3. Food insecurity and SDG.

Table 3. Food security issue and SDGs.

Food Security Issue	Article	SDGs
Public Distribution System (PDS) using blockchain.	[56–58]	1, 2, 3
Reduce wastage in the supply chain	[57,58]	2, 12

5.3. *Environmental Sustainability*

Sustainable farming improves agricultural productivity, ensures a sustainable natural resource base for the future, and addresses climate change and intensive exploitation of natural resources concerned with agricultural production. The food supply chain has the largest environmental footprint (i.e., carbon and water footprint). Farming is an energy-intensive process that contributes to about 17% of total greenhouse gas emissions [12] and around 70% of the water used for irrigation purposes. It also occupied nearly 38% of the Earth's total surface, higher than any other human activity [59]. Expanding agricultural land to meet food demands can lead to deforestation, resulting in additional greenhouse gas (GHG) emissions and biodiversity loss. Integrating digital technology in farming and food production will assist in reducing the environmental footprint by improving food production efficiencies through farm micromanagement and optimal utilization of storage and logistics to reduce waste. Using digital technology to increase food awareness among end consumers at retail will also facilitate more environmentally conscious purchasing behavior.

5.3.1. Carbon Footprint Tracking

Agricultural farming contributes a substantial amount of carbon emissions compared to processing, packaging, storage, and distribution in the food supply chain. Privacy-preserving, record-keeping systems to track carbon emissions are required to encourage producers to provide emission data. A blockchain-based system can track carbon footprints of food production and transportation stages. In [60], a cluster-based carbon emission record-keeping system based on blockchain was proposed to track the carbon footprint in food transportation. The information stored on the blockchain was transported produce, mileage, carbon footprint, and previous cluster information.

5.3.2. Transportation and Infrastructure Issues

Food transport is key in connecting all life-cycle stages of food. In the United States, food transport contributes around 11% of all greenhouse gas emissions during the food life cycle [61]. However, the unavailability of transport data makes it hard to estimate transport carbon dioxide emissions for each food product. In addition, the actual distribution route of the cargo from the origin to the destination is unknown. Overall GHG emissions were predicted using estimated cargo movement data between states and regions. A local food supply chain generates fewer emissions than a larger supply chain [62]. Availability of transportation data and cargo movement tracking is necessary to accurately calculate the total carbon footprint of a sole product over its entire life cycle. In [60], a blockchain-based Carbon Footprint chain was proposed to provide information on pre-consumption stages of the food life cycle (from farm to retail). For developing countries, the transportation system has several crucial issues, such as the mode of transportation, availability of temperature-controlled vehicles, high transportation costs, and lack of the right infrastructure for food storage. These issues must be resolved to improve the effectiveness of food supply chain and achieve the SDGs (Figure 4).

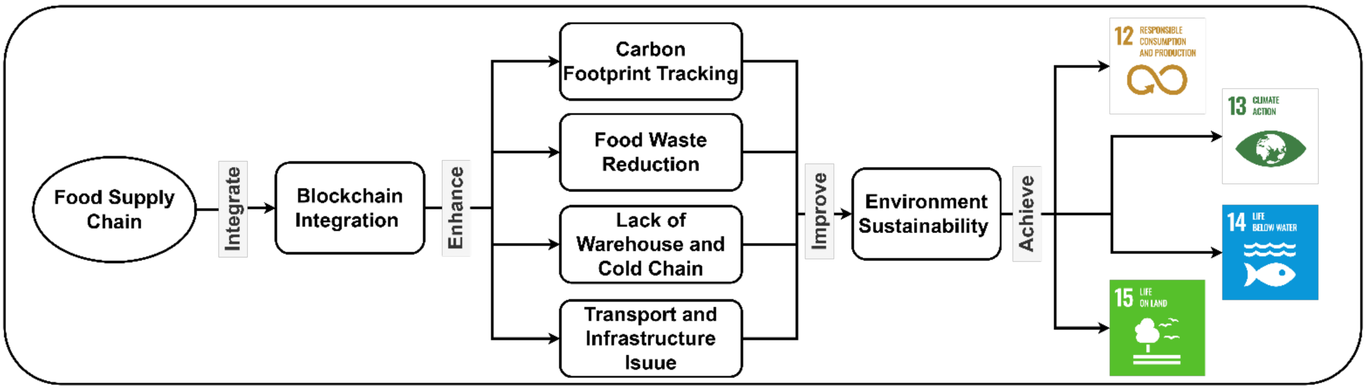

Figure 4. Food supply chain environment sustainability and SDG.

5.3.3. Food Wastage and Loss

There are several examples of food safety agencies issuing food alerts. With such a warning, much food is getting wasted. However, proper labeling and tracking systems can identify affected foods. This way, food waste can be reduced by discarding only affected foods. Another concerning area where food waste needs to be addressed is packaging. Packaging is essential in preserving and handling perishable goods to improve shelf life. In developing nations, food gets wasted because of poor packaging [63]. The UN SDG "Responsible Consumption and Production" (SDG-12) targets reducing global food loss. An efficient and transparent traceable system could help improve fish quality and reduce the risk of food loss [39]. Blockchain applications were studied using a stochastic five-level batch dispersion model in [64] (Figure 4). The objective was to reduce recall costs in cases food contamination occurred. The stochastic mathematical model was designed considering a random probability distribution of customer demand to optimize batch dispersion and improve traceability. The proposed system would provide synchronized information in real-time among supply chain partners. The availability of batch contamination information helps the supply chain partner to identify the contaminated food batch before reaching the consumer. It will save on return costs and resolve health and safety concerns.

5.3.4. Lack of Warehouse and Cold Chain

The performance of the cold supply chain in developing countries is inadequate due to the lack of infrastructure, resources, and organizational awareness. Improper storage temperatures can affect the freshness of seafood and perishable food products, leading to food loss and safety issues.

Traditional warehouses have accounting systems based on manual or centralized databases. All entries, such as arrival time, departure time, and crowd, are easy to manipulate and manipulate [65]. If food is not handled properly, this refrigerated warehouse can be the epicenter of food waste. In [66], an autonomous storage system was proposed that uses machine learning and blockchain technology to combat food waste, reducing food waste in a cost-effective, easy-to-implement, and efficient way. AI models can be used to predict sales deadlines based on the current conditions of cold stores and how long a particular product will last under the current environmental conditions to reduce food waste.

5.4. Food Trade and Policy

5.4.1. Food Trade

Food trading plays a significant role in the food supply chain. The main players in the food trading system are farmers, processors, traders, distributors, wholesalers, retailers, and consumers. Various organizations and countries have taken precautions to establish a fair-trading environment. For example, the European Commission banned unfair trading practices to safeguard medium and small-sized food and agricultural businesses. Trade in food and agricultural products is subject to many last-minute changes and urgent orders. It includes late payments for fresh produce, order cancellations at the last minute, and unilateral contract changes. The perishability of such products and the special requirements to ensure their quality makes them difficult to handle. These problems compromise the stability of the food supply chain and reduce transaction efficiency. In addition, the complexity of the transaction process, long transaction times and high transaction costs make trading even less efficient. The dynamics and uncertainties of supply and demand, the lack of clarity about the quality of fresh food, and the availability of the right amount in a timely and specific location are other factors that challenge agricultural trade development. Therefore, we need to find a solution that can protect the fairness of transactions and improve the efficiency of grocery transactions.

A consortium blockchain-based food trading system called FTSCON (Food Trading System COnsortium blockchaiN) was proposed to improve transaction security and trust issues [67]. The proposed system sets permission and authentication criteria for several roles in food trading, fulfilling privacy protection for multi-stakeholders. The optimized transaction algorithm is designed to help the user to find the right transaction object. Numerical analysis confirms the system's effectiveness in maximizing dealer profits quickly and with little computational effort. Developing a sustainable organic food trade system involves the participation of diverse combinations of organic producers, processors, distributors, retailers, suppliers, peer organizations, and individuals. In the diverse organic food supply chain, the proposed system is an efficient digital tool for traders to ensure market fairness and reduce information asymmetry. It would also improve profit for merchants helping support the system's economic value [68].

Improving small-scale farmer/producer income is one of the primary targets in achieving Zero hunger (SDG-2) and No-poverty (SDG-1). A small-scale producer can gain more profit if they have direct market access. Marketing small farmers' products are often done in arranged spaces or by intermediaries. Small farmers have less chance to market their products directly to the consumer. Farmers have fewer opportunities to sell their products directly to the consumer and earn more profit. Blockchain can connect producers and consumers and provide a trading platform for small farmers to sell their products without restrictions at lower prices and earn more profit [69] (Figure 5).

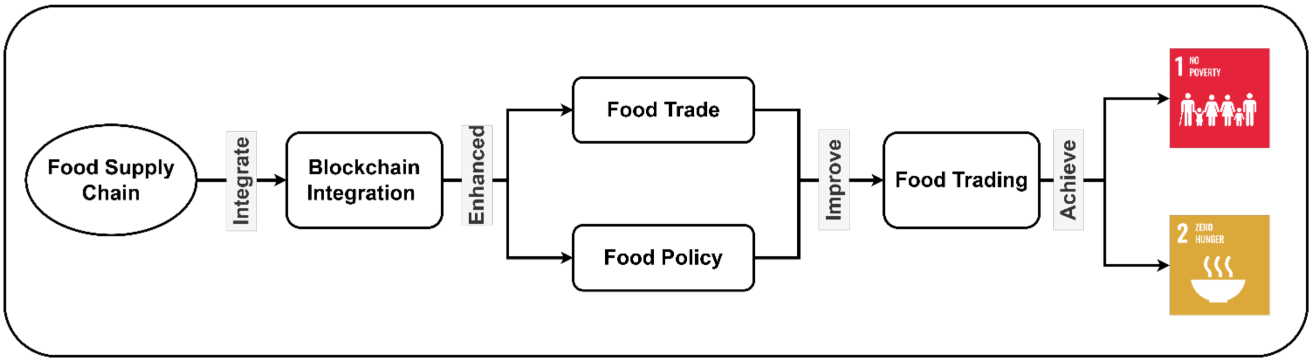

Figure 5. Food trading and SDG.

Blockchain guarantees the creation of credible supply chains for producers and consumers by allowing secure information exchange about the status of farms, product stocks and contracts. A smart contract-based payment system guarantees timely payments between supply chain actors. Further, smart contracts can automate trading. The blockchain-based trading system brings transparency, trust and security to the trading process and improves profitability without much change in production costs [25]. In [52], an image-based traceability system integrated with blockchain was proposed to provide honey keepers direct access to premium markets to earn more profit. The smart tracking system gives farmers better market access and reduces transaction costs. An asymmetric transparent information system reduces transportation costs by better coordinating between producer and processor. Information transparencies empower small-scale producers to understand buyer needs and thus have better negotiation power. The transaction cost could be reduced with a smart contract that automates the transaction process and provides protection against exploitation by big corporates [70].

5.4.2. Food Policy

Measures to improve the environmental sustainability of food production can lead to higher production costs and higher consumer prices. In other words, strategies that address some of the challenges of the triple bottom line often have synergies (positive effects) or trade-offs (negative effects) relating to other sustainability goals (Figure 5). One problem perspective for each goal over other goals may lead to unintended effects. Policymakers need to address key sustainability challenges and consider their interrelationships. In policy development, it is essential to consider the views and needs of all the stakeholders in the food supply chain, including farmers, processors, traders, consumer representatives, researchers, and environmentalists.

In developing countries, the food sectors are getting less attention during development and policy design, resulting in a lack of infrastructure and resources to achieve food security and reduce food waste. Creating a decentralized database using blockchain to gain access to data in near real-time will help policymakers. However, data inaccuracies can contribute to over-exploitation of resources and result in ecological imbalances. A blockchain-based fishing monitoring system to help regulators develop more scientific and reasonable regulatory strategies to reduce overfishing was presented in [18]. Built-in smart weighing system to increase weight accuracy while fishing that automatically records weights and transmits this information using blockchain with data transparency and verifiability. In addition, it also facilitates government agencies to control and manage ecological risk areas.

6. Discussion and Future Research Area

SDGs include an overall sustainability aspect of the world at national level, and most developing and underdeveloped countries are agricultural-based economies. Therefore, improving sustainability in the agriculture sector is crucial to achieving SDGs. With the increasing reach of information and communication technology (ICT) in recent times, it is important to use ICT effectively to achieve sustainable development goals for a food supply chain that has the highest impact on sustainability and employs the largest workforce compared to any other sector [11]. In recent times, various ICTs such as mobile, web, IoT, cloud computing, machine learning, and drone have been used in food production and distribution to improve productivity and reduce cost and environmental impact [71]. These technologies benefited in efficient use of machinery, tracking of food products, and information sharing. However, FSC still lacking in transparency and trust which impacted in improving sustainability. Blockchain is the technology that will fill these gaps.

Blockchain use cases improve various sustainability aspects in the food supply chain by bringing transparency and a trustable data system which helps in achieving SDGs such as No poverty (SDG-1), Zero hunger (SDG-2), Good health and wellbeing (SDG-3), Sustainable production and consumption (SDG-12), Climate action (SDG-13), Life below water (SDG-14), and Life on land (SDG-15).

Blockchain improves five main aspects of the agri-food industry: traceability, transparency, accountability, product labeling, and financial efficiency. Improving these aspects enhances consumer trust in the food supply chain [43]. Blockchain provides digital support for food traceability systems through data security and transparency. It enables the consumer to check history of food they are buying. Studies showed that blockchain-based traceability systems contribute to sustainable behaviors in agri-food processing, where users can also monitor and audit regulatory compliance reports which enhance transparency and accountability of farms [36]. Blockchain-based traceability systems that integrate data transparency and visibility, ensuring product authenticity and legitimacy, help in improving food safety and quality. Blockchain also provides a decentralized distributed system that removes intermediaries resulting in a direct communication channel between producer and consumer, which improves transaction efficiencies and leads to rural development and greater financial inclusion. Blockchain is a valuable digital technology that provides much-needed data transparency to support the fight against corruption, counterfeit products, and non-regulatory compliance [72].

Studies showed that blockchain along with other technology like IoT, and RFID could improve sustainability performance [35,42,49]. IoT and blockchain could be used to monitor life under sea and ecological systems to check overexploitation of sea resources by accessing transparent fishing data [73]. However, using an IoT system makes the system more transparent, efficient, and reliable, and it comes with challenges, such as the higher cost of the system. For example, in case of tracking fishing activity, IoT and blockchain integration should be made into every fishing boat in any specified area to track fishing activity; however, it is important to analyze if it is an economically viable solution or not before implementation [69].

This study showed that there are various aspects where blockchain contributed to improving the food supply chain sustainability and thus achieving SDGs. Previous studies on food supply chain and SDGs [74,75] showed that a food supply chain requires all stakeholders to contribute to achieving SDGs. Therefore, a blockchain-based system that removes information asymmetry issues in food supply chain could help in achieving in SDG. This study provides a contextual relationship between blockchain technology applications and the UN's Sustainable Development Goals. This will provide a guideline for future research on using blockchain technology in food supply chain management to consider sustainability when conducting these studies.

Blockchain has shown much promise in improving the food supply chain sustainability. However, certain factors delay its wider adoption across industries, including blockchain, a relatively new technology, and the required implementation and infrastructure cost, such as blockchain application in the public distribution system (PDS) to solve food insecurity issues by reducing corrupt practices, and better auditing practices. However, PDS is mostly implemented in low-income to middle-income countries which has low penetration of ICT, and in this scenario, if the blockchain-based system was implanted, it would not benefit a mass population and will be costly concerning the local economy [58]. Blockchain applications in the food supply chain are still in an early phase. The food industry is moving slowly along the learning curve to understand its economic benefits. Studies on blockchain-based system development focus mainly on technical aspects, but little research has been conducted on business sustainability and economic viability. Environmental and social aspects must be considered in future research at each phase of blockchain-based system development. However, its application is in an early stage, and there are various drawbacks, technical and non-technical. Blockchain use case in direct engagement of producer and consumer provides a better opportunity for the producer to earn more benefit. However, it is difficult for the technically unskilled producer to adapt to complex blockchain-based trading systems [69].

In the agri-food supply chain, private and consortium blockchain solutions were preferred to design tracking, tracing, and provenance information systems due to better scalability and data privacy than public blockchain [44]. Blockchain platform selection is important, as business performance might be impacted by selecting the wrong platform. Smart contract development is still fairly slow, although technology is evolving rapidly. However, a lack of technical understanding, potential applications and economic benefits led to slower adoption rates. Research on the potential economic impacts of blockchain integration is limited and should be considered in future research.

Most supply chain partners maintain their ICT infrastructure and software solutions in a traditional supply chain, so migrating to a new blockchain-based system could be challenging. There is currently a lack of blockchain applications, creating potential doubt in their implementation [33]. In addition to technical issues, successful adoption of blockchain technology in complex and low-profit margin food supply chains depends on costs and benefits analysis and other external factors such as consumer demand and regulatory requirements [76]. The government's lack of a formal roadmap to integrate blockchain into the food supply chain is another challenge in blockchain adoption. Food supply chain actors are not on the same page about its impact and benefits. The food supply chain is very diverse, so there is a need for some globally accepted policies and standards required to integrate blockchain. The development of a standard ontology that defines messaging standards and the data to be stored is necessary. It could be done at the national as well as international level. There is also the need to define a data interoperability policy. Other challenges include framing laws related to government agencies' roles, regulators' requirements, and data privacy [50].

Most of the studies reviewed showed that the blockchain technology improved sustainability performance. However, reviewed studies are mostly either conceptual [77] or framework [35,45], which does not provide any quantifying evidence to show blockchain benefit. Therefore, future study should focus on quantifying sustainability benefit with blockchain implementation in food supply chain. In future studies, an indicator matrix could be integrated to measure sustainability improvement.

7. Conclusions

Blockchain is a technology that works entirely and effectively only when every stakeholder in the supply chain adopts it. Blockchain-based traceability and transparency systems help food supply chain actors to build better relationships with customers, increase efficiency, and reduce risks and costs of collection in case of product recall fraud and product loss. However, challenges remain among supply chain participants, such as trust in technology, human error and fraud, governance, availability and access to commercial data, and willingness to pay for sustainable goods. Stakeholders must be encouraged to participate, share responsibilities, and act ethically. Open standards and system interoperability are important considerations when designing a sustainability information management system.

The food supply chain sector will play a major role in achieving the United Nations SDGs goal by the deadline of 2030. It is well known that food production has a major impact on the environment and is also the largest employment sector that impacts sustainability's economic and social dimensions. The food sector needs more support and better government policies to encourage producers and consumers to adopt more sustainable practices. It could be achieved by providing the latest cutting-edge technology support and increasing consumer awareness. Blockchain and other digital technologies, such as AI and IoT, could be used together to provide a transparent and reliable sustainability information system. However, all these technologies require expert implementation and integration, which can be difficult for SMEs. In addition, good training platforms are crucial for training non-specialized people to use embedded digital technology.

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References

1. FAO. *The Future of Food and Agriculture—Trends and Challenges*; Food and Agriculture Organization, United Nations: Rome, Italy, 2017. Available online: http://www.fao.org/3/i6583e/I6583E.pdfFAo (accessed on 22 July 2022).
2. Trienekens, J.; Zuurbier, P. Quality and safety standards in the food industry, developments and challenges. *Int. J. Prod. Econ.* **2008**, *113*, 107–122. [CrossRef]
3. Bhat, R.; Jõudu, I. Emerging issues and challenges in agri-food supply chain. In *Sustainable Food Supply Chains*; Accorsi, R., Manzini, R., Eds.; Academic Press: Cambridge, MA, USA, 2019; pp. 23–37. [CrossRef]
4. Kroll, C.; Warchold, A.; Pradhan, P. Sustainable Development Goals (SDGs): Are we successful in turning trade-offs into synergies? *Palgrave Commun.* **2019**, *5*, 140. [CrossRef]
5. FAO. *Trade and Markets Division, Trade reforms and food Security: Conceptualizing the Linkages*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2003. Available online: https://www.fao.org/3/y4671e/y4671e.pdf (accessed on 26 July 2022).
6. Henchion, M.; Hayes, M.; Mullen, A.M.; Fenelon, M.; Tiwari, B. Future Protein Supply and Demand: Strategies and Factors Influencing a Sustainable Equilibrium. *Foods* **2017**, *6*, 53. [CrossRef]
7. Bager, S.L.; Singh, C.; Persson, U.M. Blockchain is not a silver bullet for agro-food supply chain sustainability: Insights from a coffee case study. *Curr. Res. Environ. Sustain.* **2022**, *4*, 100163. [CrossRef]
8. Kumar, A.; Kumar, S. A systematic review of the research on disruptive technology—Blockchain. In Proceedings of the 2020 5th International Conference on Communication and Electronics Systems (ICCES), Coimbatore, India, 10–12 June 2020; pp. 900–905. [CrossRef]
9. Buterin, V. *A Next-Generation Smart Contract and Decentralized Application Platform; White Paper*; Ethereum Foundation (Stiftung Ethereum): Zug, Switzerland, 2014.
10. Von Hagen, O.; Manning, S.; Reinecke, J. Sustainable Sourcing in the Food Industry: Global Challenges and Practices. *Mod. Ernaehrung Heute Off. J. Food Chem. Inst. Assoc. Ger. Confect. Ind.* **2010**, *4*, 1–9. Available online: https://papers.ssrn.com/abstract=1678472 (accessed on 3 May 2021).
11. FAO. *Food Outlook—Biannual Report on Global Food Markets: November 2019*; Food & Agriculture Organization: Rome, Italy, 2019.
12. FAO. *Emissions Due to Agriculture. Global, Regional and Country Trends 1990–2018*; Food and Agriculture Organization, United Nations: Rome, Italy, 2020; p. 18. Available online: https://www.fao.org/3/cb3808en/cb3808en.pdf (accessed on 30 June 2022).
13. Sharma, Y.K.; Mangla, S.K.; Patil, P.P.; Liu, S. When challenges impede the process: For circular economy-driven sustainabi-lity practices in food supply chain. *Manag. Decis.* **2019**, *57*, 995–1017. [CrossRef]
14. Bánáti, D. Consumer response to food scandals and scares. *Trends Food Sci. Technol.* **2011**, *22*, 56–60. [CrossRef]
15. Kendall, H.; Kuznesof, S.; Dean, M.; Chan, M.-Y.; Clark, B.; Home, R.; Stolz, H.; Zhong, Q.; Liu, C.; Brereton, P.; et al. Chinese consumer's attitudes, perceptions and behavioural responses towards food fraud. *Food Control.* **2018**, *95*, 339–351. [CrossRef]

16. Charlebois, S.; Schwab, A.; Henn, R.; Huck, C.W. Food fraud: An exploratory study for measuring consumer perception towards mislabeled food products and influence on self-authentication intentions. *Trends Food Sci. Technol.* **2016**, *50*, 211–218. [CrossRef]
17. Tsoukas, V.; Gkogkidis, A.; Kampa, A.; Spathoulas, G.; Kakarountas, A. Enhancing Food Supply Chain Security through the Use of Blockchain and TinyML. *Information* **2022**, *13*, 213. [CrossRef]
18. Hao, Z.; Mao, D.; Zhang, B.; Zuo, M.; Zhao, Z. A Novel Visual Analysis Method of Food Safety Risk Traceability Based on Blockchain. *Int. J. Environ. Res. Public Heal.* **2020**, *17*, 2300. [CrossRef]
19. Engels, S.V.; Hansmann, R.; Scholz, R.W.; Hansmann, R. Toward a Sustainability Label for Food Products: An Analysis of Experts' and Consumers' Acceptance. *Ecol. Food Nutr.* **2010**, *49*, 30–60. [CrossRef]
20. Stevens, G.C.; Johnson, M. Integrating the supply chain . . . 25 years on. *Int. J. Phys. Distrib. Logist. Manag.* **2016**, *46*, 19–42. [CrossRef]
21. Siddaway, A. What is a systematic literature review and how do I do one. *Univ. Stirling* **2014**, *I*, 1.
22. Crosby, M.; Pattanayak, P.; Verma, S.; Kalyanaraman, V. Blockchain technology: Beyond bitcoin. *Appl. Innov.* **2016**, *2*, 6–10.
23. Tian, F. An agri-food supply chain traceability system for China based on RFID & blockchain technology. In Proceedings of the 2016 13th International Conference on Service Systems and Service Management (ICSSSM), Kunming, China, 24–26 June 2016. [CrossRef]
24. Ospina, A.V.; Heeks, R. ICTs and climate change adaptation: Enabling innovative strategies, UK Strategy. *Strateg. Brief-1 Clim. Chang. Innov. ICTs Proj.* **2011**, *17*, 1–9.
25. Stranieri, S.; Riccardi, F.; Meuwissen, M.P.; Soregaroli, C. Exploring the impact of blockchain on the performance of agri-food supply chains. *Food Control.* **2020**, *119*, 107495. [CrossRef]
26. Khan, P.W.; Byun, Y.-C.; Park, N. IoT-Blockchain Enabled Optimized Provenance System for Food Industry 4.0 Using Advanced Deep Learning. *Sensors* **2020**, *20*, 2990. [CrossRef]
27. Tayal, A.; Solanki, A.; Kondal, R.; Nayyar, A.; Tanwar, S.; Kumar, N. Blockchain-based efficient communication for food supply chain industry: Transparency and traceability analysis for sustainable business. *Int. J. Commun. Syst.* **2021**, *34*, e4696. [CrossRef]
28. Manning, L.; Soon, J.M. Development of sustainability indicator scoring (SIS) for the food supply chain. *Br. Food J.* **2016**, *118*, 2097–2125. [CrossRef]
29. Djama, M.; Fouilleux, E.; Vagneron, I. Standard-Setting, Certifying and Benchmarking: A Governmentality Approach to Sustainability Standards in the Agro-Food Sector. In *Governing through Standards: Origins, Drivers and Limitations*; Ponte, S., Gibbon, P., Vestergaard, J., Eds.; Palgrave Macmillan: Basingstoke, UK, 2011; pp. 184–209. Available online: http://agritrop.cirad.fr/561648/1/document_561648.pdf (accessed on 24 October 2022).
30. Trienekens, J.H.; Wognum, P.M.; Beulens, A.J.M.; van der Vorst, J.G.A.J. Transparency in complex dynamic food supply chains. *Adv. Eng. Inform.* **2012**, *26*, 55–65. [CrossRef]
31. Rogerson, M.; Parry, G.C. Blockchain: Case studies in food supply chain visibility. *Supply Chain Manag. Int. J.* **2020**, *25*, 601–614. [CrossRef]
32. Banerjee, A. Blockchain with IOT: Applications and use cases for a new paradigm of supply chain driving efficiency and cost. In *Advances in Computers*; Kim, S., Deka, G.C., Zhang, P., Eds.; Elsevier: Amsterdam, The Netherlands, 2019; Volume 115, pp. 259–292. [CrossRef]
33. Vivaldini, M. Blockchain in operations for food service distribution: Steps before implementation. *Int. J. Logist. Manag.* **2021**, *32*, 995–1029. [CrossRef]
34. Biscotti, A.; Giannelli, C.; Keyi, C.F.N.; Lazzarini, R.; Sardone, A.; Stefanelli, C.; Virgilli, G. Internet of Things and Blockchain Technologies for Food Safety Systems. In Proceedings of the 2020 IEEE International Conference on Smart Computing (SMARTCOMP), Bologna, Italy, 14 September 2020; pp. 440–445. [CrossRef]
35. Arena, A.; Bianchini, A.; Perazzo, P.; Vallati, C.; Dini, G. BRUSCHETTA: An IoT Blockchain-Based Framework for Certifying Extra Virgin Olive Oil Supply Chain. In Proceedings of the 2019 IEEE International Conference on Smart Computing (SMARTCOMP), Washington, DC, USA, 15 June 2019; pp. 173–179. [CrossRef]
36. Zhang, X.; Sun, P.; Xu, J.; Wang, X.; Yu, J.; Zhao, Z.; Dong, Y. Blockchain-Based Safety Management System for the Grain Supply Chain. *IEEE Access* **2020**, *8*, 36398–36410. [CrossRef]
37. Musah, S.; Medeni, T.D.; Soylu, D. Assessment of Role of Innovative Technology through Blockchain Technology in Ghana's Cocoa Beans Food Supply Chains. In Proceedings of the 2019 3rd International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT), Ankara, Turkey, 11–13 October 2019; pp. 1–12. [CrossRef]
38. Liu, S.; Hua, G.; Kang, Y.; Cheng, T.E.; Xu, Y. What value does blockchain bring to the imported fresh food supply chain? *Transp. Res. Part E Logist. Transp. Rev.* **2022**, *165*, 102859. [CrossRef]
39. Feng, H.; Wang, W.; Chen, B.; Zhang, X. Evaluation on Frozen Shellfish Quality by Blockchain Based Multi-Sensors Monitoring and SVM Algorithm During Cold Storage. *IEEE Access* **2020**, *8*, 54361–54370. [CrossRef]
40. Perez, D.; Risco, R.; Casaverde, L. Analysis of the implementation of Blockchain as a mechanism for digital and transparent food traceability in Peruvian social programs. In Proceedings of the 2020 IEEE XXVII International Conference on Electronics, Electrical Engineering and Computing (INTERCON), Lima, Peru, 12–14 August 2020; pp. 1–4. [CrossRef]
41. Mondragon, A.E.C.; Mondragon, C.E.C.; Coronado, E.S. Feasibility of Internet of Things and Agnostic Blockchain Technology Solutions: A Case in the Fisheries Supply Chain. In Proceedings of the 2020 IEEE 7th International Conference on Industrial Engineering and Applications (ICIEA), Bangkok, Thailand, 16–18 April 2020; pp. 504–508. [CrossRef]

42. Yang, L.; Liu, X.-Y.; Kim, J.S. Cloud-based Livestock Monitoring System Using RFID and Blockchain Technology. In Proceedings of the 2020 7th IEEE International Conference on Cyber Security and Cloud Computing (CSCloud)/2020 6th IEEE International Conference on Edge Computing and Scalable Cloud (EdgeCom), New York, NY, USA, 1–3 August 2020; pp. 240–245. [CrossRef]
43. Cao, S.; Powell, W.; Foth, M.; Natanelov, V.; Miller, T.; Dulleck, U. Strengthening consumer trust in beef supply chain traceability with a blockchain-based human-machine reconcile mechanism. *Comput. Electron. Agric.* **2021**, *180*, 105886. [CrossRef]
44. Katsikouli, P.; Wilde, A.S.; Dragoni, N.; Høgh-Jensen, H. On the benefits and challenges of blockchains for managing food supply chains. *J. Sci. Food Agric.* **2021**, *101*, 2175–2181. [CrossRef]
45. Malik, S.; Kanhere, S.S.; Jurdak, R. ProductChain: Scalable Blockchain Framework to Support Provenance in Supply Chains. In Proceedings of the 2018 IEEE 17th International Symposium on Network Computing and Applications (NCA), Cambridge, MA USA, 1–3 November 2018; pp. 1–10. [CrossRef]
46. Tse, D.; Zhang, B.; Yang, Y.; Cheng, C.; Mu, H. Blockchain application in food supply information security. In Proceedings of the 2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Singapore, 10–13 December 2017; pp. 1357–1361. [CrossRef]
47. Mao, D.; Wang, F.; Hao, Z.; Li, H. Credit Evaluation System Based on Blockchain for Multiple Stakeholders in the Food Supply Chain. *Int. J. Environ. Res. Public Health* **2018**, *15*, 1627. [CrossRef]
48. Wu, H.; Cao, J.; Yang, Y.; Tung, C.L.; Jiang, S.; Tang, B.; Liu, Y.; Wang, X.; Deng, Y. Data Management in Supply Chain Using Blockchain: Challenges and a Case Study. In Proceedings of the 2019 28th International Conference on Computer Communication and Networks (ICCCN), Valencia, Spain, 29 July–1 August 2019; pp. 1–8. [CrossRef]
49. Stach, C.; Gritti, C.; Przytarski, D.; Mitschang, B. Trustworthy, Secure, and Privacy-aware Food Monitoring Enabled by Blockchains and the IoT. In Proceedings of the 2020 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops), Austin, TX, USA, 23 March 2020; pp. 1–4. [CrossRef]
50. Iftekhar, A.; Cui, X.; Hassan, M.; Afzal, W. Application of Blockchain and Internet of Things to Ensure Tamper-Proof Data Availability for Food Safety. *J. Food Qual.* **2020**, *2020*, 1–14. [CrossRef]
51. Tao, Q.; Cui, X.; Huang, X.; Leigh, A.M.; Gu, H. Food Safety Supervision System Based on Hierarchical Multi-Domain Blockchain Network. *IEEE Access* **2019**, *7*, 51817–51826. [CrossRef]
52. Runzel, M.A.S.; Hassler, E.E.; Rogers, R.E.L.; Formato, G.; Cazier, J.A. Designing a Smart Honey Supply Chain for Sustainable Development. *IEEE Consum. Electron. Mag.* **2021**, *10*, 69–78. [CrossRef]
53. Lo, S.K.; Xu, X.; Wang, C.; Weber, I.; Rimba, P.; Lu, Q.; Staples, M. Digital-Physical Parity for Food Fraud Detection. In *International conference on Blockchain*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 65–79. [CrossRef]
54. Hua, J.; Wang, X.; Kang, M.; Wang, H.; Wang, F.-Y. Blockchain Based Provenance for Agricultural Products: A Distributed Platform with Duplicated and Shared Bookkeeping. In Proceedings of the 2018 IEEE Intelligent Vehicles Symposium (IV), Changshu, China, 26–30 June 2018; pp. 97–101.
55. Shahid, A.; Almogren, A.; Javaid, N.; Al-Zahrani, F.A.; Zuair, M.; Alam, M. Blockchain-Based Agri-Food Supply Chain: A Complete Solution. *IEEE Access* **2020**, *8*, 69230–69243. [CrossRef]
56. Thakare, P.; Dighore, N.; Chopkar, A.; Chauhan, A.; Bhagat, D.; Tote, M. Implementation of Block Chain Technology in Public Distribution System. In *Hybrid Intelligent Systems*; Springer: Cham, Switzerland, 2020; pp. 210–219. [CrossRef]
57. Pawar, R.S.; Sonje, S.A.; Shukla, S. Food subsidy distribution system through Blockchain technology: A value focused thinking approach for prototype development. *Inf. Technol. Dev.* **2021**, *27*, 470–498. [CrossRef]
58. Shwetha, A.N.; Prabodh, C.P. Blockchain—Bringing Accountability in the Public Distribution System. In Proceedings of the 2019 4th International Conference on Recent Trends on Electronics Information, Communication & Technology (RTEICT), Bangalore, India, 17–18 May 2019; pp. 330–335. [CrossRef]
59. FAO. *Water for Sustainable Food and Agriculture*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2017; Available online: https://www.fao.org/3/i7959e/i7959e.pdf (accessed on 26 August 2022).
60. Shakhbulatov, D.; Arora, A.; Dong, Z.; Rojas-Cessa, R. Blockchain Implementation for Analysis of Carbon Footprint across Food Supply Chain. In Proceedings of the 2019 IEEE International Conference on Blockchain (Blockchain), Atlanta, GA, USA, 14 July 2019; pp. 546–551. [CrossRef]
61. Weber, C.L.; Matthews, H.S. Food-Miles and the Relative Climate Impacts of Food Choices in the United States. *Environ. Sci. Technol.* **2008**, *42*, 3508–3513. [CrossRef]
62. Burgess, P.; Sunmola, F.; Wertheim-Heck, S. Blockchain Enabled Quality Management in Short Food Supply Chains. *Procedia Comput. Sci.* **2022**, *200*, 904–913. [CrossRef]
63. Wohner, B.; Pauer, E.; Heinrich, V.; Tacker, M. Packaging-Related Food Losses and Waste: An Overview of Drivers and Issues. *Sustainability* **2019**, *11*, 264. [CrossRef]
64. Maity, M.; Tolooie, A.; Sinha, A.K.; Tiwari, M.K. Stochastic batch dispersion model to optimize traceability and enhance transparency using Blockchain. *Comput. Ind. Eng.* **2021**, *154*, 107134. [CrossRef]
65. Kumar, A.; Liu, R.; Shan, Z. Is Blockchain a Silver Bullet for Supply Chain Management? Technical Challenges and Research Opportunities. *Decis. Sci.* **2020**, *51*, 8–37. [CrossRef]
66. Nikish Kumar, S.V.; Balasubramaniam, S.; Sanjay Tharagesh, R.S.; Kumar, P.; Janavi, B. An Autonomous Food Wastage Control Warehouse: Distributed Ledger and Machine Learning based Approach. In Proceedings of the 2020 11th International Conference on Computing, Communication and Networking Technologies (ICCCNT), Kharagpur, India, 1–3 July 2020. [CrossRef]

67. Mao, D.; Hao, Z.; Wang, F.; Li, H. Novel Automatic Food Trading System Using Consortium Blockchain. *Arab. J. Sci. Eng.* **2018**, *44*, 3439–3455. [CrossRef]
68. Lin, X.; Chang, S.-C.; Chou, T.-H.; Chen, S.-C.; Ruangkanjanases, A. Consumers' Intention to Adopt Blockchain Food Traceability Technology towards Organic Food Products. *Int. J. Environ. Res. Public Health* **2021**, *18*, 912. [CrossRef]
69. Enescu, F.M.; Ionescu, V.M. Using Blockchain in the agri-food sector following SARS-CoV-2 pandemic. In Proceedings of the 2020 12th International Conference on Electronics, Computers and Artificial Intelligence (ECAI), Bucharest, Romania, 25–27 June 2020; pp. 1–6. [CrossRef]
70. Kumarathunga, M. Improving Farmers' Participation in Agri Supply Chains with Blockchain and Smart Contracts. In Proceedings of the 2020 Seventh International Conference on Software Defined Systems (SDS), Paris, France, 20–23 April 2020; pp. 139–144. [CrossRef]
71. Kayikci, Y.; Subramanian, N.; Dora, M.; Bhatia, M.S. Food supply chain in the era of Industry 4.0: Blockchain technology implementation opportunities and impediments from the perspective of people, process, performance, and technology. *Prod. Plan. Control* **2020**, *33*, 301–321. [CrossRef]
72. Tiscini, R.; Testarmata, S.; Ciaburri, M.; Ferrari, E. The blockchain as a sustainable business model innovation. *Manag. Decis.* **2020**, *58*, 1621–1642. [CrossRef]
73. Rana, R.L.; Tricase, C.; De Cesare, L. Blockchain technology for a sustainable agri-food supply chain. *Br. Food J.* **2021**, *123*, 3471–3485. [CrossRef]
74. Djekic, I.; Batlle-Bayer, L.; Bala, A.; Fullana-I-Palmer, P.; Jambrak, A.R. Role of the Food Supply Chain Stakeholders in Achieving UN SDGs. *Sustainability* **2021**, *13*, 9095. [CrossRef]
75. Jacob-John, J.; D'Souza, C.; Marjoribanks, T.; Singaraju, S. Synergistic Interactions of SDGs in Food Supply Chains: A Review of Responsible Consumption and Production. *Sustainability* **2021**, *13*, 8809. [CrossRef]
76. Lowry, G.V.; Avellan, A.; Gilbertson, L.M. Opportunities and challenges for nanotechnology in the agri-tech revolution. *Nat. Nanotechnol.* **2019**, *14*, 517–522. [CrossRef]
77. Saurabh, S.; Dey, K. Blockchain technology adoption, architecture, and sustainable agri-food supply chains. *J. Clean. Prod.* **2020**, *284*, 124731. [CrossRef]