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# The Potential of Blockchain Technology in the Transition towards Sustainable Food Systems

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**Abstract:** Food systems are both contributing to and affected by environmental degradation and climate change. The transition towards resilient and sustainable food systems is essential to ensure food security and minimise negative environmental impacts. Innovative technologies can accelerate this transition. Blockchain technology (BCT) is attracting attention as it can deliver transparency to complex global food supply chains and has the potential to guide current food production towards better sustainability and efficiency. This case study investigated the opportunities that BCT can offer to food supply chains. Qualitative interviews with eight main BCT providers were conducted to evaluate the current state of BCT and put it into perspective by mapping out advantages, disadvantages, incentives, motives, and expectations connected to its implementation in global food systems. A thematic analysis showed that, while BCT was considered beneficial by all interviewees, uptake is slow due to high implementation costs and the lack of incentives for companies throughout the food chain from farms to food industry and retail. Results further revealed that the advantages of BCT go beyond communication of trustworthy information and development of closer producer–consumer relationships. In fact, it can provide the opportunity to decrease food waste, enhance working conditions throughout the supply chain, and promote sustainable consumption habits. As BCT may be increasingly used in the food supply chain, the results give a basis for future research that may leverage both qualitative and quantitative methods to examine actors' behaviours. Also, the importance of improving user experiences through functional applications and software to facilitate the adoption of the technology is stressed.

**Keywords:** blockchain; sustainability; food systems; food supply chains; transparency; agri-food; traceability

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## 1. Introduction

With rapid population growth and damaging anthropogenic influences on nature, the likelihood of overshooting the Earth's capacity to regenerate is high, and ambitious goals for reductions in negative environmental impacts have been set at a global scale [1–3]. The agri-food sector is a considerable contributor to climate change and one of the sectors most affected by its consequences [4]—for example, through greenhouse gas emissions—while being severely influenced by climate change [5]. The agri-food sector is also affected by the fact that it induces losses in biodiversity on which future agriculture may depend [6]. Other challenges to a sustainable food future are issues related to, for example, healthier eating; soil and water management; climate change effects such as drought, heat stress, and flooding; diminishing yields; and compromised food security [1,7–10]. The issue of food waste is also a concern, for about one third of all food produced is lost or wasted annually on a global scale, which comes at a cost for society (e.g., wasted resources), and has financial implications for businesses in the food chain (e.g., inefficiencies or loss of reputation due to damaged or spoiled products) [11]. In parallel, there is increasing consumer interest in ethical and sustainable consumption as environmental awareness in society increases [12].

New concepts for future food systems aim at circularity, with improved food waste management and closed nutrient cycles, and at minimising food waste by careful transportation and storage and by maintaining the cold chain in distribution [13]. Developments within the modern food system have resulted in the concentration of production within a few large transnational corporations, which dominate the agricultural inputs, distribution, and retail sectors [14,15]. These corporations impose a strong influence on food system governance [16,17], for example through their role in "shaping the dominant agricultural model adopted around the world" [15] (p. 28), disconnecting global causes from local impacts, and by dominating "agricultural policy agenda at both national and international levels" [16] (p. 532).

Food supply chains are commonly long, scattered, and opaque, with a substantial distance between food producers and consumers, which leaves the latter with limited insight into the consequences of their purchasing behaviour [15,18]. Hence, traceability in the food supply chains is a central concern. In addition, parts of the food supply chains suffer from lack of digitalisation [15], which can be a consequence of insufficient or unequal digital resources, skills, and motivation [19]. Annosi et al. [20] also pointed this out, showing that barriers for digitalisation in the food chain included difficulties to coordinate with partners that were different in size, had incompatible 'digital mindsets', or made different strategic choices on digitalisation. Hence, these differences, and the generally low level of digitalisation, may result in inefficient processes and increased susceptibility to human error, a lack of trust and a high risk of food fraud [15]. Food-fraud incidents in particular have become a global food-system challenge, and 'food scandals' occasionally emerge, e.g., the horse meat scandal in Europe in 2013 where horse meat in processed food products was labelled as beef, or when conventional produce is fraudulently labelled as organic [21]. Lack of transparency and trust in current food chains also leads to major concerns about food quality and safety, loss of reputation and financial damage [12]. Opacity also poses a financial risk [22]. Due diligence challenges in modern food supply chains mainly arise due to missing or fraudulent data, incompatibility of data systems used by the different actors and time-consuming paper-based processes [23]. Meanwhile, there is a higher environmental awareness of consumers and pressure from policy-makers and investors, that have increased the need for more trustworthy and accurate data in food supply chains [4,23]. Arguably, food supply chains are increasingly shaped by consumer interests and rising demand for transparency [24].

The Food and Agriculture Organization (FAO) of the United Nations (UN) recognises that sustainable food value chains require access to information for all parties involved and stresses the critical importance of a functioning governance structure [8,25]. The European Commission has identified increasing transparency as an important feature for all actors involved in the food supply chain, so that each actor can easily access the necessary information on the sustainability of a product [26]. A transition to sustainable and more resource-efficient food systems is a necessity. A "Great Food Transformation" entailing structural change on multiple levels has been called for [9]. Technology-led innovations can substantially mitigate environmental deterioration and also dominate research and policy agendas [27].

One of the means identified to increase sustainability and transparency in food systems is blockchain technology (BCT), which could offer advantages to food supply chain management such as transparency, traceability [28], and data security [29]. Implementation of BCT is still in its infancy and the extent to which food system sustainability can be improved by BCT has yet to be determined, but as pointed out by Antonucci et al. [30] and Ratta et al. [31], the technology is promising and has potential for applications in several sectors.

The aims of this study were to identify the potential of BCT for aiding a transition towards sustainable food systems and to shed light on its practical implementation and potential in food supply chains. As BCT is expected to improve sustainable supply-chain management, this work sought to provide insights into its practical use, thereby supporting the overall sustainability of the food system, by assessing the following two research questions: (1) What are the opportunities and challenges to implementing BCT in current food systems? (2) How can BCT facilitate transition towards more sustainable food systems? These questions were addressed by applying a qualitative research approach involving interviews with experts working with BCT providers for food system actors.

## 2. Theoretical Considerations

### 2.1. Sustainable Food Systems

A common definition of food systems encompasses the entire range of actors and their activities and relates them to the broader economic, societal, and natural environments in which they are embedded, while a sustainable food system is defined as delivering food security and quality that does not compromise future generations' access to a sustainable food supply [32]. However, food-system analyses to date have mainly assessed issues relating to food security [33,34] and environmental impacts, e.g., in life cycle analysis [18,34]. The Food System Framework proposed by the Institute of Food Science and Technology (IFST) [35] embeds the food supply chain in the three dimensions of sustainability and integrates it in a broader scope of sustainability. The framework points out key areas aiming to develop knowledge, policies, initiatives, and guidance in favour of transition towards more sustainable food systems. The framework is divided into six thematic areas: (1) Resource risks and pressures; (2) Healthy sustainable diets; (3) Circular economy and sustainable manufacturing; (4) Novel production systems and ingredients; (5) Decent work and equitable trade; and (6) Transparency, traceability, and trust.

### 2.2. BCT and Sustainable Food Systems

Since the publication of the white paper by Nakamoto [36] about Bitcoin and secure financial transactions between two parties without the need for an intermediary, there have been intense discussions on cryptocurrencies [37]. The underlying technology is widely recognised as a potential game-changer for certain sectors and disruptive for many other sectors. Known as distributed ledger technology or blockchain technology (BCT), it is defined as a decentralised immutable ledger able to store, process, validate, and authorise transactions (*ibid.*). Metaphorically, each transaction entered in the blockchain at a specific time is stored in a single unit, known as block. Each block contains a digital fingerprint of the user that inserts the data, which is called hash. Additionally, a cryptographical identification marker of the preceding block is added. In that way, a blockchain is a linear, chronological continuity of stored information, visible for any (authorised) user in real-time. Once a block is added to the chain, it is securely stored as an immutable, transparent, and permanent feature of the blockchain [38]. The immutability and decentralisation of data differentiate BCT from conventional data-handling systems. Consequently, trust and transparency between parties are increased [27], while anonymity and data security are ensured [38]. BCT is proving to be a valuable technology in different sectors and increasingly so in the food sector [39]. However, there is still limited knowledge of BCT in the agri-food context. Most studies of BCT in the agri-food sector have focused mainly on software aspects [30]. The first wave of blockchain applications in the food sector addressed issues of trust, transparency, and information sharing among stakeholders in the food chain [40], which will likely play an important role in traceability management for agri-food [41,42].

### 2.3. Conceptualising a Sustainable Food System Framework in the Context of BCT

An adapted version of the IFST model was used as the analytical framework in this study (Figure 1). This model, the Sustainable Food System Framework, outlines the BCT-based food supply chain in the centre of key areas of sustainable food systems. The food supply chain is circularly embedded in the three dimensions of sustainability—the environment, society and the economy—and their overlapping areas. In the modified framework, the original six themes in the Food System Framework are revised to: (1) Resilience and resource efficiency; (2) Sustainable and healthy diets; (3) Circular economy; (4) Profitability and efficiency; (5) Sustainable supply chains and fair trade; and (6) Transparency, traceability, and trust. Examples of the food system's impact and dependence on each sustainability area are shown in Figure 1 and described below.

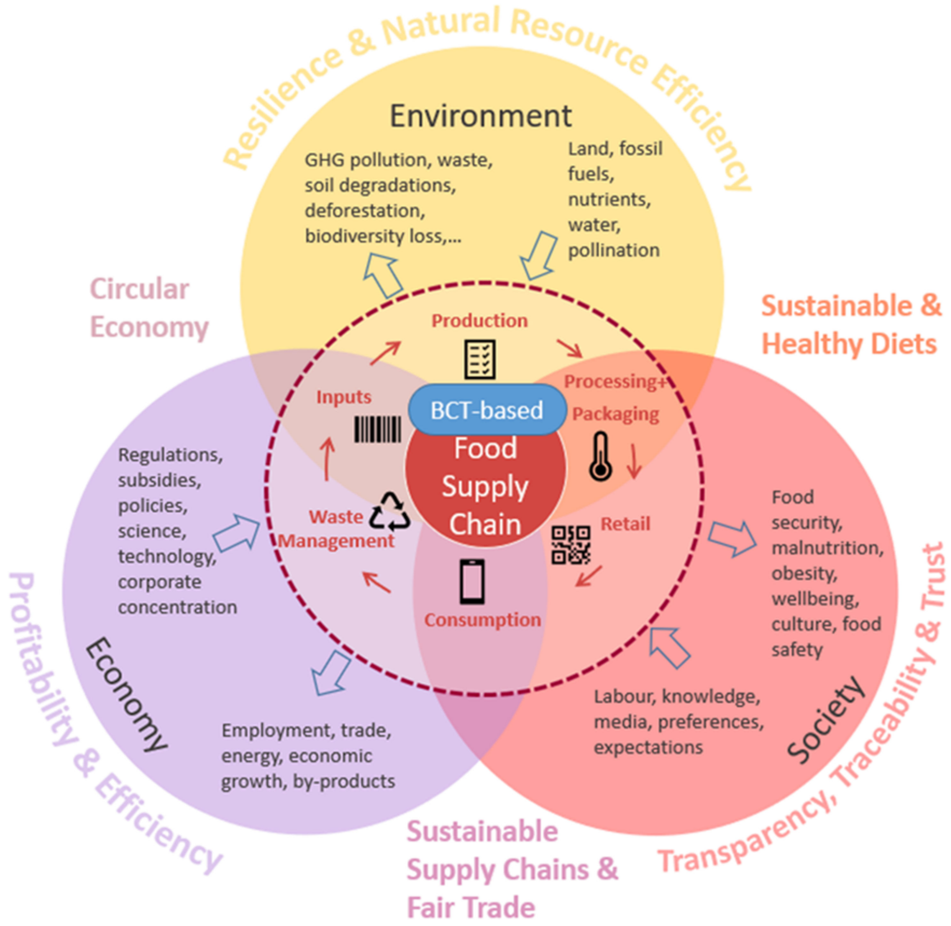


**Figure 1.** The Sustainable Food System Framework and potential influences from blockchain technology (BCT). Own conceptualisation based on IFST [35].

### 2.3.1. Resilience and Resource Efficiency

Using BCT, data on environmental conditions can be captured along the whole food value chain to facilitate the identification of risks and pressures. BCT can store and share data, e.g., on humidity and temperature during transportation and storage, which can help prevent foodborne disease outbreaks and recalls [12]. Individualised perishability dates (adapted to the conditions under which the food has been produced, transported, and stored) on food products provided by BCT can prevent household food waste [43]. More efficient resource planning and transportation, enabled by increased visibility and transparency, can reduce environmental impacts on food systems [44].

### 2.3.2. Sustainable and Healthy Diets

BCT can convey information about specific attributes of food products to the consumer, enabling informed decision making and aligning with demands to purchase healthy, ethical, and sustainable products. Hence, consumers can make well-informed and careful decisions that are less influenced by the media [45]. BCT could perhaps also be used to avoid food fraud and ensure food safety, thereby protecting public health [46–48].

#### 2.3.3. Circular Economy

BCT promotes better planning and can improve circular flows in production [27]. Responding to the increased amount of food packaging, consumers, it has been shown, can be motivated to recycle food containers if receiving crypto-tokens is an incentive [27]. The European Union action plan for a circular economy acknowledges the importance of BCT in accelerating circularity, de-materialising the European economy, and promoting an entrepreneurial culture [26]. Food waste mitigation by preventing recalls is another way to improve circularity in food systems. As pointed out by Kouhizadeh, Zhu, and Sarkis [49], issues such as resource waste and biodiversity losses can be managed and resolved through BCT.

#### 2.3.4. Profitability and Efficiency

BCT is part of a transition towards more data-driven agriculture and food production in general [10]. It is recognised that big data, Internet of Things (IoT), Artificial Intelligence (AI) and machine learning, together with physical innovations (e.g., sensors, machines), are transformative for food systems [43], facilitating decision-making by actors along the food chain [50]. Economic sustainability can be improved by reducing costs and enhancing efficiency as direct consequences of disintermediation, while reducing market uncertainty and inefficiency [51,52]. As BCT is able to record different dimensions of a food product, it eliminates the need for a third party to manage the data centrally [27]. Smart contracts can facilitate certification management and help process improvement by automated verification of the data [53].

#### 2.3.5. Sustainable Supply Chains and Fair Trade

The most important advantage of BCT lies in the increased transparency, traceability, and trust it provides [54]. If data on specific attributes of a food product can be transparently passed on to the consumer, this can enable informed decision-making and, by verification of certificates, satisfy consumer demand to purchase ethical and sustainable products [45,54]. It has been shown that ethical working conditions as part of social sustainability can be verified by consumers directly, once supply chains become transparent [44]. Shorter supply chains, a possible outcome of BCT, may also increase farmers' status and foster the development of their community [50].

#### 2.3.6. Transparency, Traceability and Trust

BCT is expected to restore consumer trust, improve sustainability and detect and prevent corruption and fraudulent activities by supply-chain members [27]. It reduces the current information asymmetry in centralised supply chains and supports increased equality in bargaining power among parties [52]. Through the greater transparency, regulators can easily and regularly monitor markets to prevent collusion [52]. As suggested by Köhler and Pizzol [55], a direct impact of BCT is to increase trust within the supply chain. A fast reaction to the increased consumer and government demand for greater transparency in food supply chains will likely benefit those companies which adopt BCT [51]. However, there has been no standardisation on the kind of data that need to be made available [56,57]. Governance is seen as pivotal for successful and sustainable implementation of the technology, but requires structural and organisational changes [56].

## 3. Research Approach

A single case study approach [58] was applied. This is seen as an appropriate method when exploring complex topics, as it builds on previous research by providing additional data and insights [59]. Technology providers of BCT in food supply chains were set as the unit of analysis. This was motivated by the aim of this study to identify the potential of BCT for aiding transition towards sustainable food systems, whilst there are yet few examples on implementation of BCT throughout food-supply chains [56]. Hence, frontline technology providers targeting the food sector were deemed to be the actors with the most holistic insights on the implementation of BCT in the food system. This study did not focus on a specific geographical area, nor on a specific food commodity. This is because of the lack of broad use of BCT in the food sector, but the study's broad parameters allowed it to identify challenges and possibilities across the whole sector and from different locations.

### 3.1. Data Collection and Analysis

Data were obtained in eight interviews with experts working in firms providing BCT-based platforms intended for the food sector (Table 1). Interviewees were purposively selected for their extensive knowledge and experience of practical use of BCT. All those selected work closely with various players in food supply chains and have insights into the requirements and challenges connected with implementation of BCT in food supply chains. The sampling procedure followed three consecutive steps: (1) Firms offering BCT for supply chain management were identified in the background research phase; (2) the websites of potential firms were checked and firms that fulfilled the criteria of offering a BCT solution for food supply chains were listed; and (3) 14 potential interviewees were contacted, resulting in five positive responses. During the interviews, new potential participants were recommended (snowball sampling), resulting in three additional participants.

**Table 1.** Details of the interviewees.

| Code | Function | Firm/Code | Details | Country |
|---|---|---|---|---|
| R1 | Project and Marketing Manager | C1 | C1 is a tech start-up offering customisable blockchain-based technology that can be implemented in existing (food) supply chains to improve transparency and traceability, food safety and efficiency | Germany |
| R2 | Former Manager, now self-employed | C2 | C2 is a BCT solution for all food supply chain players, enhancing transparency via real-time shared data. R2 is now developing a start-up around ecosystem services certificates, helping farmers who provide ecosystem services with an additional income from trading certificates. | Netherlands |
| R3 | Co-Founder, CEO | C3 | This start-up is a technology provider creating a more agile, efficient and certain supply chain for food. It captures data using IoT sensors, secures the data with BCT and uses AI to create real-time supply chain visibility, apprising all supply chain partners of issues as they arise and predicting issues before they occur. | USA |
| R4 | Functional Expert | C4 | C4 is a company by and for the commodities trading and shipping industry. It was established by some of the largest corporations worldwide in agricultural commodities trading, e.g., in grain and soy. The platform aims at modernising and increasing efficiency in agri-food supply chains based on BCT. | Switzerland |
| R5 | Head of Projects and Impact | C5 | C5 is a social enterprise and a merger of two start-ups. It is providing smallholder farmers with mobile technologies to access information, financing and the global market, thus strengthening their position in the food chain. It uses cloud, AI and BCT. | India |
| R6 | Chief Marketing Officer | C6 | C6 is a start-up that digitises fresh food produce. It works with digital IDs to track products along the supply chain and to share the information with the actors in the supply chain and consumers via QR codes. It is based on AI and BCT and aims at collaborative commerce and increased visibility of supply chain actions. | Singapore |
| R7 | International Business Developer | C7 | C7 is a fast-growing start-up that uses BCT as end-to-end tracking solution to increase internal supply chain traceability and to provide transparency for consumers via QR codes on products. | France |
| R8 | Co-Founder | C8 | C8 is a young tech company working with a combination of technologies in order to increase visibility in agri-food (especially seafood) supply chains. | USA |

The interviews followed a semi-structured interview guide comprised of seven thematic areas: (1) the interviewee's expertise and area of work; (2) the current use of BCT in food supply chains; (3) the effect of BCT on actors in the food supply chain; (4) the potential of BCT in transforming food systems; (5) the role of BCT in power distribution in food supply chains; (6) the role of governance and regulations; and (7) consumer aspects of BCT. The interviews were conducted through different digital communications platforms (Zoom, Webex, and Skype), lasted for around 30–60 min, and were recorded upon the interviewee's agreement. The recorded interviews were transcribed and coded, and thematic analysis was applied for systematic identification and organisation of the empirical findings [60]. In the coding process, passages of the transcripts were transferred into a table (with ordinary word processing software) according to the six identified areas outlined in the conceptual analytical framework based on the IFST [35] (Figure 1); this process enabled the consistent interpretation of data, a variety of research questions, and the interviewees' experiences [61]. For competitive reasons and data protection, the names of the firms are anonymised.

### *3.2. Quality of Collected Data*

To ensure the quality of the study, construct validity, internal and external validity, and reliability were assessed [58]. The explorative nature of the study did not allow for the assessment of causal relationships, and therefore internal validity was not accounted for. Construct validity was ensured by the semi-structured interview guide, which was subsequently coded and thematically analysed to minimise the influence of the researchers on the findings. External validity ensures transferability of results, which in this study was accounted for by interviewing firms operating in the same sector in similar functions across three continents. Respecting boundary conditions, the results reflect transferable findings in an emerging field of study. Data triangulation and the use of multiple sources of information (such as interviews in combination with an extensive literature review) increased the reliability of the analysis [62]. Finally, validity was increased by meticulous documentation of data collection and processing. Personal reflections during the research process were recorded and member checking (sending back interview summaries to the participants; [62]) was done to give the interviewees an opportunity to clarify statements.

## **4. Results and Discussion**

### *4.1. BCT and Its Applications in Food Systems*

The results obtained are presented and discussed thematically below. Analysis of the findings followed the conceptual framework in Figure 1.

#### 4.1.1. Resilience and Natural Resource Efficiency

The interviewees emphasised that collection of sustainability-relevant data is increasing, and a number of start-ups are entering the field of measuring production-specific parameters for improving yields and sustainability (e.g., availability of soil enzymes, fertiliser, pesticide and water use). A problem pointed out is that the data are not fully utilised and do not reach the consumer. Although BCT offers the possibility to include relevant data, such as antibiotic use in livestock farming, nitrate levels in food, carbon footprint, or local sourcing, the current application of BCT rarely considers this type of data. The case firms reported encouraging producers to fully disclose relevant information, but a current lack of regulation, high expenditure, and issues of competition prevent them from sharing data. The lack of specification and guidelines means that producers can decide to reveal only marketing and branding information. Since they can choose what data to share, or not to share, they only showcase positive aspects, without having to justify negative aspects. Surprisingly, the potential for recording product-related and environmental data, as pointed out by [12,44], is currently not utilised in practice. Most interviewees claimed that environmental considerations are not the driver for BCT implementation in the food sector, as indicated by the following statement: "The thing we want to solve is accuracy and efficiency. Our core idea is not about sustainability or quality parameters. That's something which will probably get added". However, there were contrasting examples of current uses of BCT with regard to environmental sustainability, including sharing production data with agronomists for optimisation, supply-chain actors, and eventually consumers, as one interviewee exemplified: "We work with the really specific farm-level information, which we are able to integrate. If producers want to say that their produce is sourced locally or that they are reducing their carbon footprint or pesticide use, we're able to ( . . . ) show things like [that]".

#### 4.1.2. Sustainable and Healthy Diets

According to the interviewees, there is no direct connection between healthy and sustainable diets and BCT. They pointed out that transparent information on provenance and production methods can have an impact on product choices as consumer awareness of animal welfare and environmental outcomes increases. They also mentioned that BCT can help consumers adopt a healthier and more sustainable diet if information is shared with them and they have an interest in changing their diet. Sharing information with consumers to enable them to make more informed decisions is a key concern, as pointed out by [38], but some interviewees clarified that consumers do not want to know everything about a food product even if they claim to expect full transparency. One respondent described the dilemma as follows: "We should only show consumers things that will benefit them and that they are able to absorb and understand". Supply-chain actors, on the other hand, would require access to different information like shipping dates, storage details, etc. In their business, pre-selection of information given to the consumer is performed by the firms, which decide what they want to share. A typical application would be a QR code on the packaging that delivers transparent information verified by BCT.

#### 4.1.3. Circular Economy

The interviewees emphasised that all actors in the supply chain need to be involved to create a more circular economy. By monitoring food quality throughout the journey, food waste can be prevented, and money and resources saved, which is in line with the application of BCT in other areas (e.g., [27]). One interviewee gave a practical example of how BCT can contribute to circularity by reducing food waste through facilitating a reverse, intelligent market for soon-to-expire food that retailers can buy from wholesalers at a discounted price if they know they can sell it within a specific timeframe. Several interviewees highlighted that communicating the benefits to consumers via a QR code can create more societal awareness. Most importantly, according to one respondent, the claims made by a producer can be verified with BCT, which increases their significance. None of the interviewees could point out a comprehensive cradle-to-cradle solution integrating both the input sector and waste or recycling systems. According to [27], BCT can improve the transition to a circular economy in food systems, but this was not an expressed aim of any of the case companies. This indicates that the circular economy concept and BCT application in food systems are rather new and the connection seems to be unprioritised for now. For the future, one respondent anticipates merged platforms: "Right now, platforms have a single functionality, like one platform providing insight on where the food comes from, one platform for logistics, one platform for better information on how food is produced [ . . . ]. What we will be seeing in the future is what is called a system of systems. These platforms will be put together in some form and provide information across the entire food chain and on multiple functionalities."

#### 4.1.4. Profitability and Efficiency

The interviews revealed that current food supply chains are still largely paper-based and reliant on manual work, and thus inefficient and time-consuming. In particular, long international and trans-continental supply chains were identified to suffer from lacking intergovernmental consensus on data sharing and the required technical equipment.

However, according to the interviewees, governments are increasingly demanding a change towards more digitised commodity trading to facilitate and enhance efficiency in the food sector. This is also in line with the general development of more data-driven agriculture and food production [12]. Previous research has pointed out that BCT has strong potential to increase economic sustainability [51,52], but there is no consensus on the relative cost of BCT. Half the respondents reported that, although BCT itself is not too expensive, implementation in existing data-handling systems is rather resource-intensive for small and medium-sized companies. Such companies will only become interested when benefits clearly outweigh the costs required for adoption of BCT. Changing the system would require everyone in the chain to open up their firewalls to place a blockchain node, a step that is only feasible for larger companies and that is, according to one interviewee, "the key for why only large businesses can afford to do this [now]".

The implementation of BCT can help to save money by avoiding recalls, and it could be a risk-mitigating device that outweighs the initial costs of changing an existing system and maintaining a new data-handling system. The interviewees suggested that BCT can make the system "*safer and much quicker*", but a constraint is poor internet access in large parts of the world. There was also no consensus on whether technology will become more affordable in the future. While consumer demand for more transparency is driving the implementation of BCT, this seems to be dependent on its effect on food prices, as one interviewee noted: "Someone has to pay for implementing a new system. If the cost is passed on to the consumers, they need to see the added value". BCT can lead to lower food prices, as it can save costs by recall prevention, while the higher costs originating from more sustainable food production can be balanced out by the higher efficiency and stable prices.

#### 4.1.5. Sustainable Supply Chains and Fair Trade

The interviewees strongly believed that the broad use of transparency-enhancing technologies like BCT will change the power distribution and increase fairness among trading partners. This is well in line with the general view on BCT [52,55]. However, how the system is designed and applied will be important, as one interviewee highlighted: "If we share product information, provenance and condition data in an egalitarian way in which everyone owns the data, and no one owns the data, it creates widespread business benefits for all supply chain players, not just the big ones. If you can make it so that it is affordable and understandable [ . . . ], it can really change the system." BCT has the potential to disrupt corporate concentration and power imbalances, but one respondent warned: "while blockchain has the potential to provide insights and information to each and every one, we are in real danger of it being dominated by the current large parties that are already dominating the market".

The extent to which BCT can change the dynamics in supply chains was exemplified by one interviewee working with smallholder farmers in developing countries: "[Our aim is] to increase their livelihood standards and help them to connect to direct markets, because [ . . . ] the farmers [today] lack affordability and accessibility of information and are often dispersed and in remote rural villages". Technologies can bridge the information gap and at the same time erase middlemen who withhold information from farmers and make profits without adding value to the food product. Another interviewee stated specifically that "one of the learnings from this entire human-digital economy is the reduction of the middle effect" and thus the potential to shorten supply chains, enabling farmers to sell their produce directly to buyers. BCT could also have the potential to devolve more power towards end-consumers. In general, the shift is seen from the dominant party to farmers and consumers, as one interviewee exemplified: "As soon as you start knowing the source, it [ . . . ] means the consumers know more about where [the food] came from and it gives [the producers] more power, because all of a sudden, they are being seen".

#### 4.1.6. Transparency, Traceability, and Trust

For the most common theme, intersecting with all sustainability dimensions, there was broad consensus that delivering transparency is the main benefit of BCT in food systems. This is in line with results from other studies (e.g., [27,55]). The interviewees recognised that retailers are experiencing pressure from consumers, who are demanding more clarity on food origin and provenance. Issues of sustainability and food fraud are already driving consumers to request reliable certificates of origin. However, transparency within the supply chain and transparency for the consumer are regarded separately. According to one interviewee, there is currently a lack of transparency, created by antiquated paper systems, data silos, differing regulatory requirements between different countries, and a natural fear among supply chain companies of losing competitive advantage through transparency. This explains why digitalisation in agri-food supply chains has lagged behind that in other industries. The interviewees pointed out that much of the data captured on farm level today is not utilised to improve overall supply chain management. Several respondents explained that BCT provides the ability to trace back information, helping to identify weak points in the supply chain and thus helping the supplier and other actors in assuring that the product paid for meets expectations and requirements and that complaints can be addressed correctly.

### *4.2. BCT and the Transition towards a More Sustainable Food System*

The current food system faces multiple sustainability challenges, as pointed out by the International Panel on Climate Change [3] and the FAO [8,25]. The findings presented in this study show how the application of BCT can facilitate change towards more sustainable food systems. An overview of the use of BCT, including how it relates to specific sustainability issues important in food-system transformation, is provided in Table 2.

The interviewees reported stronger impacts of BCT implementation on the economic and social sustainability dimensions than on the ecological/environmental dimension. This may indicate that the implementation of BCT in the food area is mainly driven by firms outside the food system with core competencies in the area of BCT and information management, rather than food production. Nevertheless, several applications relating to production, resource, and waste management were pointed out. It is clear that the technology can promote a more circular economy in the food and agriculture sector (e.g., [13]). As a tool for communicating information between actors in the food chain, BCT may be an important complement to existing certification schemes that currently delimit the amount of information. An issue is whether BCT will enhance consumer access to all information, or whether a dominant actor (e.g., the retailer or the technology provider) will restrict the information recorded. BCT is likely not the decisive technology for a more sustainable food system but may assist in the transition towards more data-driven agriculture and food production in general [24]. Rather, an ecosystem of technologies (e.g., IoT, AI, machine learning) can together enhance decision making in food systems and lead to more sustainability. The success of BCT will rely on creating an integrated and holistic system of these emerging technologies, which are substantially underrepresented in the agri-food sector compared to other sectors and which have seen a low degree of investment [43].

In accordance with the findings, food-system impacts from the implementation of BCT can be depicted using the Sustainable Food System Framework [35], shown in Figure 2. The BCT has been identified to have strong direct implications for three of the six sustainability pillars, mainly for 'Transparency, traceability, and trust', attributing it the biggest arrow in the figure. As BCT can strengthen supply-chain players, the direct impact on 'Sustainable supply chains and fair trade' is portrayed as the second strongest impact. After successful implementation, BCT has the potential to increase 'Profitability and efficiency' as the third main effect. As for the other pillars, the impact of BCT is identified to be less strong and caused indirectly by its strengths to deliver immutable, decentralised, and transparent information. By that, resources can be attributed more accurately while recalls, food waste, and food fraud can be prevented. Furthermore, communicating trustworthy information to consumers increases their knowledge and subsequently can promote more sustainable and healthy purchasing decisions.

**Table 2.** Current Challenges for food systems and the use of blockchain technology (BCT).

| Food System Framework Category | Importance in Food System Transformation | Use of BCT |
|---|---|---|
| Resilience and resource efficiency | Food systems contribute substantially to climate change<br>Highly reliant on functioning ecosystems<br>Food insecurity as consequence of climate change | Store and share data from agricultural precision technologies<br>Prevent waste through individualised perishability dates<br>More efficient planning via increased transparency |
| Sustainable & healthy diets | Plant-based diets are more environmentally friendly<br>Consumer education and preferences are crucial for rethinking the food system<br>Globally higher demand for energy-intensive foods<br>Environmental awareness in society is increasing<br>Higher demand for sustainable products | Provide the consumer with transparent and verified data for better decision making |
| Circular economy | Food waste minimisation<br>Nutrient recycling | Better planning can improve recycling<br>Motivation via crypto tokens<br>Traceability helps to identify flaws in the supply chain and prevent food contamination and spoilage |
| Profitability and efficiency | Food waste and GHG emissions are inefficiencies in food systems<br>Lack of digitalisation<br>Long and complex supply chains<br>Opacity/Transparency | Reduced costs (via disintermediation) increase economic sustainability<br>Minimisation of human error<br>Safe data transfer reduces risk<br>Disintermediation of supply chains |
| Sustainable supply chains and fair trade | Concentration of power to a few multinational corporations<br>Absence of cooperation and policies on international level | Immutability and reliability of data can detect and prevent corruption and increase trust in the supply chain<br>BCT reduces information asymmetry and improves equality in bargaining power<br>Collusion can be monitored and prevented<br>Verification of ethical working conditions and fair trade |
| Transparency, traceability, and trust | Distance between producers and consumers<br>Environmental impacts of food are rarely visible to the consumer<br>Lack of trust in brands and labels<br>Food safety concerns | BCT increases transparency for all supply chain members<br>Transparency increases trust, brand image and decision-making |

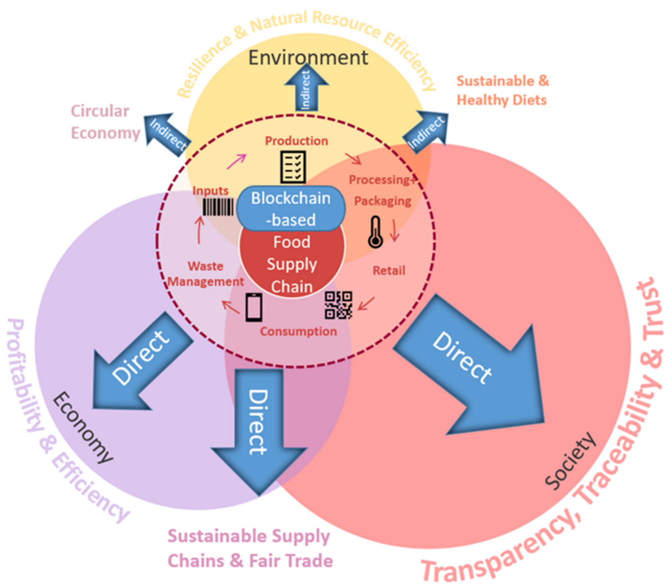


**Figure 2.** Impact of blockchain on food system sustainability (Own elaboration based on the results, applied on the Sustainable Food System Framework [35]).

### 4.3. Implications for Practice

This study revealed that tech companies find BCT beneficial, while the fact that the case companies are growing fast indicates the relevance and legitimacy of the business model. On the other hand, the respondents reported that many competitors have left the market already. This is in line with other research findings suggesting a discrepancy between technical feasibility and operational constraints, as well as false expectations [56,63]. The present study showed that BCT is only one in a set of tools that will eventually make food supply chains more sustainable. Surprisingly, this has not been addressed in previous research. Viewing BCT as a part of an integrated, real-time shared data ecosystem (rather than as an isolated technology) is crucial to attributing accurate value to the technology and preventing ambiguous expectations.

Businesses are struggling with implementation of BCT for several reasons: First, the novelty and complexity of the technology have led to misconceptions about the term BCT and the capacity of the technology. While the interviewees noted that BCT has not lived up to (unrealistic) expectations, its real potential was still seen as game-changing and it was considered to be well worth implementing in food supply chains. Hence, some of the interviewees reported that their companies actively avoid mentioning BCT to avoid misconceptions and scepticism, revealing the discrepancy between what companies and the general public see in the technology. However, all respondents reported good experiences with the technology from their own perspective and based on customer feedback. Second, while the technology itself is not necessarily expensive, implementation is still costly. This is a barrier particularly for small and medium-sized businesses, and this corroborates the finding by [20] that there are difficulties to coordinate partners that are different in size. Incorporating BCT into existing data-handling systems will require human resources and system changes for all supply chain players. Further, this points out the importance that BCT software and applications are tested using a quality software and user-experience analysis to ensure that they are user friendly and functional. This is to make it accessible for users as a way to overcome unequal digital resources, skills, and motivation among actors in the food chain [19]. Finally, the choice of BCT architecture is fundamental for the openness of supply chain members to implementing a BCT system. Since food supply chains include the international trade of commodities, as pointed out by [56], there is a need for assurances that confidential data will be handled securely and will not lead to competitive disadvantages.

### 4.4. Limitations and Future Research

Due to differences in their company's global distribution, respective target markets and size, and to the different posts they hold in their company, the interviewees were not directly comparable. Nevertheless, they provided similar estimates of the place of BCT in sustainable food supply chains. The interviewees' expertise in the agri-food sector also varied, and their position outside food supply chains can be perceived as both a benefit and a drawback for the quality of the findings of this study. Furthermore, their work with multiple actors without having to increase a single player's profit gave a certain diversity in responses. Incorporating the feedback of other actors across one food supply chain could provide further valuable insights into motives, expectations, and outcomes regarding the use of BCT and paint a more holistic picture of advantages and disadvantages offered by the technology. Other similar technologies can be expected to emerge, and time will tell whether they become a permanent feature of food supply chains.

This study focused on technology providers, but did not include the whole supply chain, as there are currently few examples on where BCT has been implemented in the whole chain [56]. It would be useful to continue the research, as BCT becomes more widespread in the food chain, with the design of BCT services, user experiences of software and applications, and other practical issues related to current documentation and certification systems. Future research should include qualitative assessments of firms throughout the chain, including upstream supply chain players (e.g., farmers and smaller agri-food firms), as their use of the technology must function in their daily operations. But as BCT becomes more widely used in the food chain, quantitative studies with food industry and other actors would also be needed to deepen the current understanding of the topic. There may also be a need to improve industry standards on data sharing and transparency, while accounting for the role of policies. Integrated systems using AI and IoT together with the BCT can provide further resource efficiency and lower the use of input supplies in food production, an area that needs further research. Finally, comparing the environmental sustainability (with tools like life cycle assessment) of food in conventional systems and in BCT-facilitated supply chains could facilitate quantitative reasoning on the value that BCT can add to more sustainable food systems.

## 5. Conclusions

The acknowledged benefits of BCT are enhanced visibility and traceability, as well as the immutability of records. This can lead to the creation of trust, efficiency, and to some extent fairness in today's long and complex food supply chains. Enabled by increased transparency, the educational effect for consumers can shift demand towards more sustainable products, strengthen the position of farmers, and disseminate good practices. In general, communicating verified and trustworthy information on food provenance, combined with extra information on, for example, recipes or perishability dates, can increase awareness and aid the transition towards a more sustainable food system. From an environmental perspective, however, the advantage of BCT itself seems to be restricted to resource savings due to recall prevention and better planning of the supply chain. In order to convince all actors along the supply chain of the benefits of BCT, despite initially high costs of implementation, more governmental or societal pressure at global level might be an inevitable requirement.

The modified Sustainable Food System Framework applied in this study proved to provide a stable basis for analysing the contributions of BCT to sustainability in the food system. BCT was found to have an impact on all sustainability areas identified as important for food systems transition. Thus, BCT has potential if added to existing supply-chain management practices, but this will require the collective engagement of all stakeholders. Given the global disparity in access to internet and data, and the lack of continuous digitalisation of food supply chains, full adoption of BCT in the food system remains a challenge.

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