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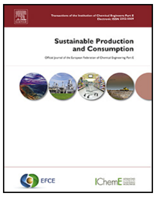

Review Article

The intersection of blockchain technology and circular economy in the agri-food sector[1]

Ashkan Pakseresht [a,*], Ali Yavari [b], Sina Ahmadi Kaliji [c], Karin Hakelius [d]

[a] *Brunel Business School, Brunel University London, Uxbridge, Middlesex UB8 3PH, United Kingdom*
[b] *Swinburne University of Technology, School of Science, Computing and Engineering Technologies, Melbourne, Australia*
[c] *Alma Mater Studiorum-University of Bologna, Department of Agricultural and Food Sciences, Bologna, Italy*
[d] *Swedish University of Agricultural Sciences, Department of Economics, Uppsala, Sweden*

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ABSTRACT

A transition towards a circular economy within the agri-food sector requires the improvement of efficiency in resource utilization, the prevention of food loss or waste, whilst adopting regenerative agricultural practices. In addition to the technical challenges, the agri-food industry needs to address the food safety concerns resulting from biomass recycling processes. Increasingly, blockchain technology is gaining traction, moving towards more sustainable and precision agriculture. The blockchain is a decentralized, immutable, and shared database that records the provenance of digital assets, making it a suitable platform for traceability and food supply chain management. Despite its growing importance, the existing literature regarding these themes and the empirical evidence of blockchain-based solutions for a circular economy is rather fragmented. This paper offers a scoping review regarding the role of blockchain technology in the transition towards a circular food system. A total of 44 papers published in peer-reviewed journals were reviewed to identify new scientific insights into the application of blockchains within the agricultural sector. The results indicate that blockchain technology has a great potential in reducing food loss through optimized eco-efficiency (e.g., digitalization and integration with the Internet of Things) and by alleviating asymmetric information (by increasing transparency and reducing dependence on intermediaries). However, in the case of recycling efficiency, despite its potential, there remains a paucity of evidence regarding the use of blockchain technology in improving the residual valorization processes. Furthermore, there is a stream of literature focusing on the ability of blockchain-enabled traceability (e.g., for organic production or supply chain management). Yet, the role of blockchain traceability in the monitoring of risks from recycled biomass and the reporting of the sustainability performance in the supply chain has received scant attention within research literature. These results provide insights for supply chain management operations with the view of shifting towards a circular economy whilst also suggesting an agenda for future research areas.

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[*] Corresponding author.
E-mail addresses: ashkan.pakseresht2@brunel.ac.uk (A. Pakseresht), mail@aliyavari.com (A. Yavari), Sina.ahmadikaliji@unibo.it (S.A. Kaliji), karin.hakelius@slu.se (K. Hakelius).

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1. Introduction

With population growth and an increasing demand for food, the pressure on natural resources has increased exponentially. For the food supply chain, this means that more food needs to be produced sustainably while upholding elevated standards of food quality (Fraanje et al., 2019; Ghisellini et al., 2016). The Circular Economy (CE) is being increasingly acknowledged as one of the ways to overcome this challenge (Harris et al., 2021; Ojha et al., 2020; Oliveira et al., 2021). The transition towards circular food supply chains means the prevention of food loss, the enhancement of resource utilization productivity, and the development of regenerative natural systems (Ojha et al., 2020; Oliveira et al., 2021). The literature summarizes the main interconnected strategies of the CE within various so-called “R” frameworks (Demestichas and Daskalakis, 2020; Mhatre et al., 2021). Concerning the food supply chain, the R-framework includes the preventive strategies of “Reduce” (food surplus or inputs), “Refuse” (preventing food loss), “Reuse” (redistribution for human consumption), and “*Re*-purpose” (e.g., redistribution for animal feed use), as well as valorizing strategies, such as “Recycle” (extracting bio-components from waste) and “Recover” (recovering energy embedded in waste). “Regenerative” strategies include the agricultural practices that preserve natural resources (e.g., sustainable production, organic production, fair-trade production, etc.).

Resource efficiency will be achieved through the technological improvements that reduce the amount of inputs (such as raw materials, land, energy, and water) that are needed to produce a unit of output, as well as recycling waste and utilizing by-products. In addition, improved storage and distribution methods contribute to the prevention of post-harvest losses (Despoudi and Dora, 2020). Regenerative agricultural practices, such as conservation agriculture (e.g., zero-tillage), agroforestry (i.e., planting trees on crop farms), local food production, and organic production, ensure that the food is produced in a way that replenishes, rather than degrades, the overall health of the local ecosystem (see e.g., Duarte et al., 2019; Grant, 2017; LaCanne and Lundgren, 2018; Newton et al., 2020). However, to achieve a successful transition to the CE, it is necessary to deal with various barriers, such as poor cooperation among the food chain stakeholders, the lack of eco-efficiency in technological processes, and traceability efficacy (Ada et al., 2021).

Due to the dynamic nature of the food supply chain, the agri-food industry needs to manage multiple stakeholders and uncertain processes (Ada et al., 2021). Moreover, the CE's emphasis on waste utilization within the supply chain may raise additional trust and food safety issues. For instance, using recycled materials for food packaging may raise food safety concerns among consumers and authorities (Alamri et al., 2021; Geueke et al., 2018). Furthermore, one of the reasons for food waste on the farm level is the problem of safety hazards, such as the mycotoxin contamination of feed, antibiotic overuse in livestock disease treatments, and zoonotic disease spread (Toma et al., 2020). Therefore, food supply chains need to ensure that the use of recycled materials complies with regulatory boundaries (Newton et al., 2020).

Recently, blockchain technology has gained traction in addressing different challenges within the food supply chain (Demestichas and Daskalakis, 2020; Nandi et al., 2021; Upadhyay et al., 2021). A blockchain is a decentralized shared database that records the provenance of a digital asset (Raikwar et al., 2019). Blockchain is arguably a secure technology that can be used to support supply chain performance by increasing the transparency in transactions, integration among stakeholders, and through digitalization (Sheel and Nath, 2019).

Proponents argue that blockchain technology supports sustainable agriculture by reducing food recalls, due to more efficient traceability features, as well as determining the accuracy of carbon emissions in the supply chain due to its immutable and transparent nature (Nayal et al., 2021; Saberi et al., 2018). Demestichas and Daskalakis (2020) conducted a literature review to examine the relevance of the information and communication technology solutions (such as the Internet of Things, blockchain, digital platforms, and artificial intelligence algorithms) for the Circular Economy (CE). The authors concluded that, among these solutions, blockchain technology has a great potential to contribute to the principles of CE, such as “Reduce”, “Reuse”, and “Recycle”. In addition, it has been demonstrated that blockchain technology has the potential to eliminate counterfeits in agri-food production, as well as maintaining trust among the actors in the food supply chain (Bettín-Díaz et al., 2018; Caro et al., 2018; Galvez et al., 2018; Tian, 2016; Wamba and Queiroz, 2020). Despite its growing importance, current literature is rather fragmented concerning the themes and empirical evidence. Previous reviews to date have tended to focus on the drivers (e.g., Dutta et al., 2020; Li et al., 2021) and the barriers (Duan et al., 2020; Pandey et al., 2022; Vu et al., 2021) of blockchain adoption within the food sector, with none of these reviews providing insights into the Circular Economy. In response to this, this scoping review investigates the intersection of blockchain technology and Circular Economy in the agri-food sector. To address the research gap in the literature, the present review makes the following practical contributions; (a) demonstrates applications of blockchain-based solutions across the agri-food sector; and (b) indicates the relevancy of the blockchain technology in achieving CE within the food supply chain. In particular, this review aims to answer the question: how does blockchain technology accelerate the transition towards CE in the food supply chain? The major focus in this paper is the potential areas where blockchain implementations can contribute to CE, hence, the technical aspects fall out of the scope of the present study.

This paper is structured as follows. The current section continues by reviewing the dimensions of the CE within the food supply chain, followed by the presentation of the concepts and structures of typical blockchain technology. In Section 2, the method for data collection and analysis will be presented. Section 3 reviews the reported blockchain applications which may be potentially relevant for the CE in the agri-food sector. Section 4 discusses the theoretical significance, practical implications, limitations, and future research. Section 5 briefly concludes the study.

1.1. Circular economy in the agri-food sector

The food supply chain is facing resource scarcity and therefore, the traditional linear production approach is indisputably unsustainable (Ghisellini et al., 2016). In the linear model, resources are exploited and processed into food products, which are eventually consumed or discarded as waste (Despoudi, 2019; Despoudi and Dora, 2020; Ghisellini et al., 2016). Additionally, food supply chains are challenged through the problem of food loss due to several factors, such as poor farm management, processing problems, overproduction, and unstable markets (Timmermans et al., 2014). The complications arise in situations where unsustainable farming practices deteriorate the natural resources (FAO, 2019). Losses and waste follow the entire food supply chain, from agriculture through industrial processing and the delivery (Mirabella et al., 2014), all the way down to household consumption (see Table A1 in Appendix I, for examples of food waste/loss generated at different stages of the food supply chain). In Europe, it is estimated that about 39 % of all food is lost in primary production and 61 % wasted during the distribution and consumption (which households, service segments, and retailers are responsible for generating 42 %, 14 %, and 5 % of food waste respectively) (Mirabella et al., 2014; Rajković et al., 2020).

There is no common agreement regarding the definition of food loss and waste (see e.g., Koester, 2014; Koester and Galaktionova, 2021), however, the Food and Agriculture Organization (FAO) reports that in 2019, they distinguished food loss from food waste based on their occurrences in the food supply chain and their level of utilization. Food loss is "*all the crop, livestock and fish human-edible commodity quantities that, directly or indirectly, completely exit the post-harvest/slaughter/catch supply chain by being discarded, incinerated or otherwise disposed of, and do not re-enter in any other utilization (such as animal feed, industrial use, etc.), up to, and excluding the retail level.*" (FAO, 2019, p. 10). Food waste refers to the reduction in the quantity or quality of food that "*occurs at the consumption/demand stages*" (FAO, 2019, p. 10). Therefore, food waste is all the remaining biological material from human-edible commodity quantities that are disposed of after having entered the food supply chain for processing and consumption. Likewise, the overall biomass loss (including crop, livestock, and fish products) is referred to as "*all quantity losses (food and non-food) along the food supply chain for all utilizations (food, feed, seed, other) up to but excluding the retail to consumption level*" (FAO, 2019, p. 5). By-products are the substrates derived from the food production process (such as agriculture, forestry, marine, and animal-derived residues) where the functional components can be utilized (Galanakis, 2012; Jasch, 2008). By-products are generally inedible residuals from industrial processing or household consumption. Examples of by-products generated in the food supply chain include potato peels from starch production (Fischer and Bipp, 2005), apple and grape pomace in fruit juice processing (Kammerer et al., 2014), barn mills from oat grinding (Yu and Brooks, 2016), malt and molasses residue in sugar beet production (Fischer and Bipp, 2005), and sunflower seed or soybean residue in oil extraction (Kammerer et al., 2014; Vong and Liu, 2016).

Food loss (and waste) is both a food security concern, as well as a driver of climate change issues (Ghisellini et al., 2016), therefore, a transition towards the CE has been increasingly advocated for (Geng et al., 2013; Korhonen et al., 2018; Michelini et al., 2017). The CE is an economic model of production that optimizes the natural ecosystem through more efficient resource management, processing, handling, and recycling procedures (Demestichas and Daskalakis, 2020; Murray et al., 2017). The CE also aims to maintain food supply chain resilience, while diminishing environmental damages, without confining economic growth (Lieder and Rashid, 2016). Fig. 1 presents a summary of broad strategies to cope with food loss and waste within the realm of the CE. Broadly, CE strategies can be categorized as preventing food loss; resource efficiency (towards waste/by-products valorization); and regenerative agriculture (For details refer to e.g., Kirchherr et al., 2017; Papargyropoulou et al., 2014; Potting et al., 2017). Regenerative practices aim to preserve resources (e.g., by employing organic farming), while preventive strategies, such as 'Refuse' (e.g., preventing food loss by improving post-harvest handling), 'Reduce' (e.g., reducing demand-supply distortions and lowering surplus), 'Reuse' (e.g., using food banks for discarded food), and 'Repurpose' (e.g., redistribution for animal feed use) aims to reduce food excess or prevent food loss. Valorizing strategies such as 'Recycle' (e.g., valorizing biocomponents) and 'Recover' (e.g., incineration) transfer waste streams into bio-components or energy recovery. Although there are significant advantages of employing CE principles within food supply chains, their implementation is constrained by considerable challenges.

1.2. The blockchain as an enabler technology

As mentioned earlier, one of the main barriers for CE is the lack of traceability and transparency within the food supply chain. To tackle this challenge, and to provide the required traceability and visibility

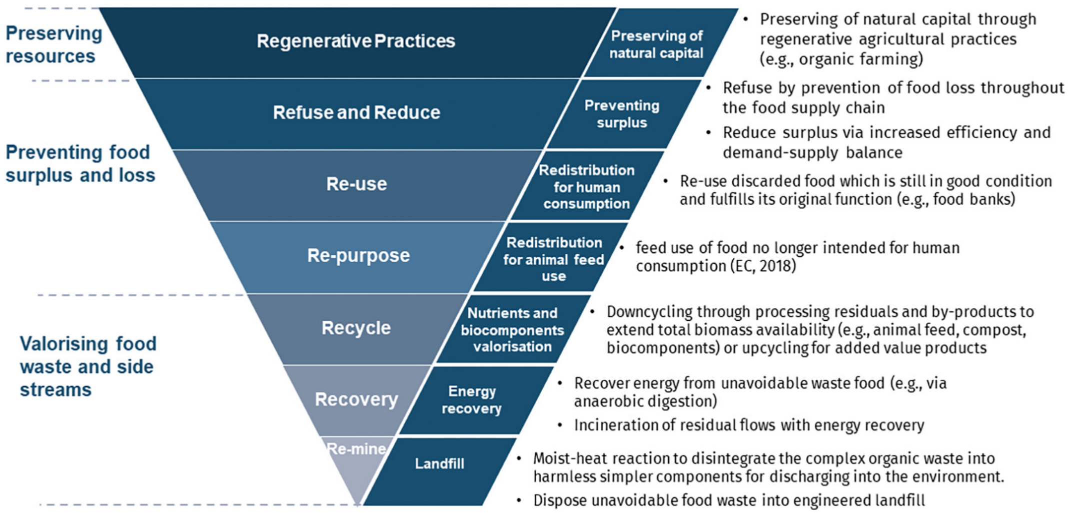

Fig. 1. The food loss/waste and surplus hierarchy and CE strategies (adapted from EC, 2018; Kirchherr et al., 2017; Papargyropoulou et al., 2014; Potting et al., 2017; Van Buren et al., 2016).

needed, it is essential to collect, store, and process the relevant data from the food supply chain. This data needs to be accessible, verifiable, and uncompromised in order to be beneficial for the CE.

Databases have been used as a mechanism to store and retrieve such data. These databases can be deployed on a single computer (i.e., a server), a data center, or can be distributed using the client-server architecture (Özsu and Valduriez, 1996).

One of the main issues with these databases is the fact that they are typically controlled by a centralized authority which has the ultimate or semi-ultimate access to the data. This makes such data management solutions not ideal for applications that deal with distributed, transparent, and tamper-resistant data. On the other hand, standard data management solutions follow the operations that allow for the updating and deleting of the data, in addition to its creation and inspection (Truică et al., 2013). These extra operations, as well as the complexity of the access and role control in such distributed environments, make them less than ideal for applications that are not following hierarchical data management roles.

CE deals with several stockholders (including entities, and contributors) that are producing, collecting, and accessing the food supply chain data that are not essentially following hierarchical data access and modification permissions. The blockchain is a method by which to store and share data in a distributed, transparent, and tamper-resistant way which creates a great opportunity for implementing CE. The blockchain system principally utilizes a chain of data and hash (e.g., SHA256) algorithms (Eastlake 3rd & Jones, 2001). Hash algorithms are widely used in several different applications, such as digital signatures and Wi-Fi security models (Dods et al., 2005; Wu et al., 2008). These functions map arbitrary size data to a fixed-sized value (e.g., 64 hexadecimal characters in the SHA256 algorithm) referred to as hash values. Hash values are the fingerprint of the data and are non-reversible. Any modification, including the addition or the removal of a part of the text/data, will change the corresponding hash value. In other words, the only possible way to regenerate any hash value is to feed the hash algorithm with the same data.

A blockchain consists of a chain of blocks and each block contains the data and a pointer to the previous block using the hash value of the prior block as illustrated in Fig. 2.

Once new data needs to be stored, a new block will be added to the free end of the chain consisting of the data and the hash value of the previous block in the blockchain. Considering that, for each block, the pointer to the preceding block along with the data is used as an input for the hash algorithm, the chain will not be maintained if there is any modification to either the data or the pointers of the prior blocks. If the blockchain is not broken, it is an assurance that the integrity of the data has not been violated.

Once the blockchain is created or extended, it will then be shared with the other peers using the peer-to-peer architecture. This allows for the sharing of data, whilst protecting and tamper-proofing the data by creating several copies of the blockchain in different locations.

The CE can benefit from blockchain technology as it provides greater transparency and traceability. In addition, blockchain technology is more of an ideal solution for storing and sharing the data collected from heterogeneous sources, whilst maintaining the integrity and tamper-proofing of the data.

One of the main drawbacks of using blockchain technology is the heavy computation required to calculate all these hash values and to maintain the chain. This will typically require a lot of processing and memory resources and can be expensive. Considering that blockchain follows a peer-to-peer paradigm, it has the potential to use distributed computing infrastructure provided by its peers. However, this might not necessarily provide the required response time for all the applications.

The performance and cost issues associated with using blockchain systems were well-known problems in the literature (Fan et al., 2020). The advancement of computing infrastructure and the emergence of new innovative paradigms, such as cloud computing and GPS-based computing, has both increased the performance and reduced the cost of utilizing blockchain technology (Vestias and Neto, 2014). It is also worth mentioning that traceability and transparency will not necessarily require immediate calculation and reporting within the Circular Economy.

2. Method

We have conducted a scoping review to provide new scientific insights into the traceability application of blockchain within the agricultural sector. A scoping review is an exploratory process of summarizing a range of evidence in order to convey the breadth and depth of a research field (Levac et al., 2010). In contrast to systematic reviews, the quality of evidence is not assessed in a scoping study (Brien et al., 2010; Grant and Booth, 2009; Rumrill et al., 2010). Instead, it addresses the broader "scope" and research questions with correspondingly more expansive inclusion criteria (Levac et al., 2010). Scoping studies are often undertaken when the feasibility of conducting a systematic review is a concern, either due to the diversity of relevant literature (varying by method, theoretical perspectives, and scopes), or a paucity of research evidence. Scoping studies are also distinguished from narrative reviews

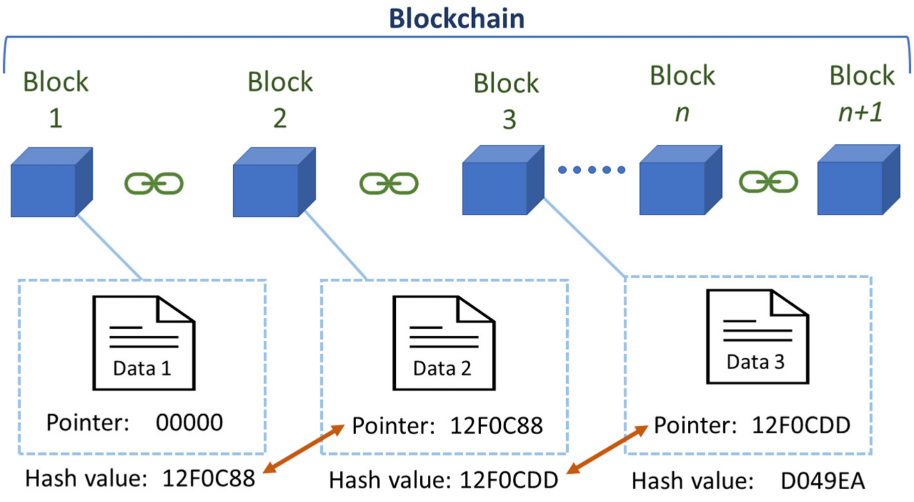

Fig. 2. A thematic representation of a blockchain database. Each added block includes data, pointer, and the hash values.

since the scoping process involves an analytical interpretation of the included literature (Davis et al., 2009). Following the guidelines provided by Arksey and O'Malley (2005) and Levac et al. (2010), this review was performed by searching through relevant literature, selecting studies, charting the data (extracting the data), as well as collating, summarizing, and reporting the results.

2.1. Data selection

Eligible papers were identified through explicit search strategies across ScienceDirect, Web of Science, and Scopus electronic databases. The following search query was used for the title, abstract, and keywords through each database: TITLE-ABS-KEY ((Blockchain) AND (Agriculture* OR Agricultural* OR Agribusiness* OR Farming* OR Food*) AND (Traceability* OR Provenance* OR Tracking*) AND (Valorize* OR Recycle* OR Circular*)).

Research papers were included if they addressed any aspect of the application of blockchain technology concerning the circular economy in the agri-food sector discussed in Section 1.2 (see Table 1 for inclusion criteria). The search covered the years 2017–2021 (until August) as research prior to this date was considered unlikely to reflect the blockchain's technological contemporary research trends. An initial screening of 2148 titles and abstracts was carried out, duplicates ($N = 240$) and those that were not related to the application of blockchain technology concerning the CE in the agri-food sector ($N = 1555$) were discarded. Papers were also excluded if they comprised of commentaries, reviews, or summary reports of otherwise untraceable research ($N = 284$). A further 30 papers were discarded, including non-peer-reviewed and conference papers. Ultimately, 39 papers were appraised as being eligible for a full-text review. The included articles were screened for cross-references and an additional 5 articles were found, resulting in 44 articles in total (see Table B1 in Appendix II). The eligibility assessment regarding the remaining articles was carried out independently by two of the authors. In cases of disagreements concerning the eligibility for inclusion, a consensus was reached through discussion and third-party arbitration. Fig. 3 shows a flow diagram of the database search and the selection of literature throughout the review.

2.2. Charting the data, summarization

A data-charting form was jointly developed by two of the authors in order to decide which variables/data to extract. The two authors independently charted the data, discussed the extracts, and continuously updated the data-charting form in an iterative process. This data-charting form contained descriptive information (such as the year of publication, country, use cases) and information about the targeted agri-food sector. The authors extracted information regarding the aims of the proposed blockchain use cases and their main findings (see Appendix III).

To collate and summarize the results, focusing on the areas where blockchain technology contributes to the CE, the authors applied a qualitative content analysis approach (Levac et al., 2010). The analysis resulted in: (1) an overview of the blockchain regarding the CE use cases across different agri-food sectors; and (2) the contribution of blockchain technology in the transition towards the circular economy within the agri-food sector.

Table 1
Inclusion and exclusion criteria.

Inclusion criteria
- Papers presenting the original results of empirical blockchain models and frameworks.
- Focus on the application of blockchain in agricultural case studies.
- Use cases with impacts on improving eco-efficiency, alleviating asymmetric information, traceability, and valorization.
- Full-text papers published in a peer-reviewed journal.
- Full-text papers written in English.

Exclusion criteria
- Sources that do not discuss the application of blockchain in agriculture.
- Non-empirical papers (e.g., conceptual pieces, editorials, and reviews), grey literature.
- Conference proceedings, book chapters, unpublished theses, reports, and white papers.
- Papers focusing on other aspects of precision agriculture,[a] such as Industry 4.0 and the Internet of Things.
- Papers concerning the application of blockchain technology for climate change adaptation and biodiversity conservation.
- Conceptual developments of blockchain technology.

[a] Precision agriculture is a farm management approach that refers to the gathering, processing and analyzing temporal, spatial and individual data acquired from information technology devices to ensure resource use efficiency and optimum production (McBratney et al., 2005; Whelan and McBratney, 2003).

3. Results

In this section, the outcomes of our scoping review on the intersection of the blockchain and the circular economy within the agri-food sector are presented. The authors start by demonstrating the main agri-food use cases across the retrieved articles followed by the outcome of the review by mapping areas where blockchain has contributed to a circular food supply chain.

3.1. Distribution of blockchain-based use cases within the agri-food sector

As depicted in Fig. 4, most blockchain use cases within the agri-food sector relates to traceability and food authentication (57 %), farm management and monitoring (16 %), followed by e-commerce and trade efficiency (11 %). Fig. 5 shows that most of the proposed blockchain solutions are related to dairy and aquatic products. China has the highest share of use case solutions developed in agriculture followed by the USA and India (see Table B1, Appendix II).

3.2. The role of blockchain in circular food systems

This section examines the literature, identifying the blockchain possibilities that may be potentially relevant for the CE within the agri-food sector. Reviewing the included articles indicates that the CE's enabling potential of blockchain in agriculture can be broadly categorized as: (1) preventive effects (e.g., alleviating asymmetric information, and optimized eco-efficiency); (2) the valorization of waste and by-products (e.g., improving residual recycling, and ex-post traceability); and (3) the enabling of regenerative strategies (e.g., facilitating ex-ante traceability) (see Fig. 6). Table 2 summarizes the potential of blockchain technology in unlashing CE strategies within the agri-food sector, which is further elaborated on in the following sections (detailed analyses are provided in Appendix III Table C1).

3.2.1. Alleviating asymmetric information

Food loss is one of the most urgent concerns in the context of the Circular Economy. Food loss is partly related to the imbalances between the supply and demand of agricultural commodities. Asymmetric information has been identified as one of the key reasons for the supply-demand imbalances and, therefore, contributes to market failures. There is a stream of literature that focuses on the asymmetric information along the food supply chain (for a review refer to Minarelli et al., 2016). Asymmetric information arises when the parties engaged in a transaction are not equally informed, which results in the inefficient allocation of resources, increased transaction costs, and market failures (Bogetoft and Olesen, 2004; Minarelli et al., 2016). For instance, the changes in market prices and consumers' demands can cause a disparity in supply and, consequently, the inability to allocate the supplied food in the market (Segre et al., 2014).

One of the major reasons for asymmetric information is related to the fact that different stakeholders in the supply chain employ different information management mechanisms, making it difficult to achieve

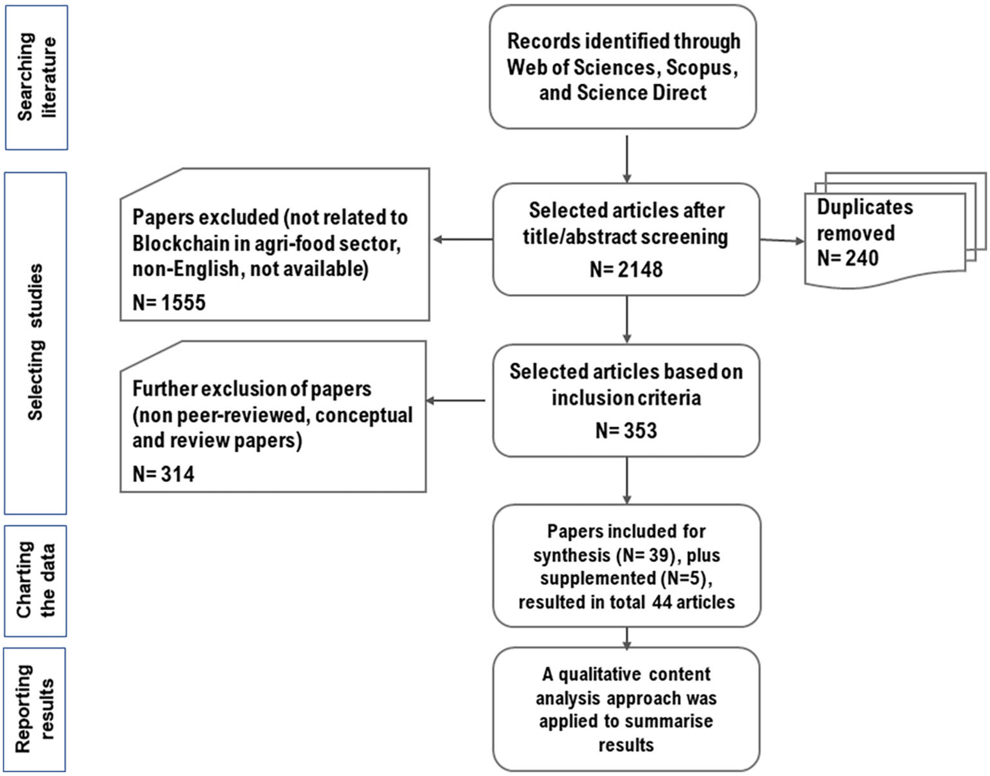

Fig. 3. The overall flow of the scoping literature search and selection.

synchronization (Hua et al., 2018). In addition, at present, the majority of transactions within the agri-food sector is centralized within third-party involvement. Generally, these centralized business systems have several drawbacks, such as the lack of trust due to information asymmetry, slow data processing, and the possibility of the shared information being tampered with. There is a growing interest in the digitization and decentralization of the agri-food systems, however, existing models are limited in their management of large data (Upadhyay et al., 2021).

Results of recent studies have shown that blockchain has the potential to resolve these problems and, therefore, reduce the issue of asymmetric information within the food supply chain (see Table 2). As depicted in Table 2, the reviewed articles (13 papers) provide evidence suggesting that blockchain technology alleviates asymmetric information by reducing the imbalances in supply and demand (e.g., Leng et al., 2018; Liu et al., 2020), the friction of information (e.g., Chen et al., 2020; Guido et al., 2020; Zhang et al., 2020a), and the need for intermediaries within the supply chain (e.g., Köhler and Pizzol, 2020; Salah et al., 2019; Syromyatnikov et al., 2020). For instance, Leng et al. (2018) investigated the application of blockchain in the agricultural supply chain and found that the blockchain system reduces disparities

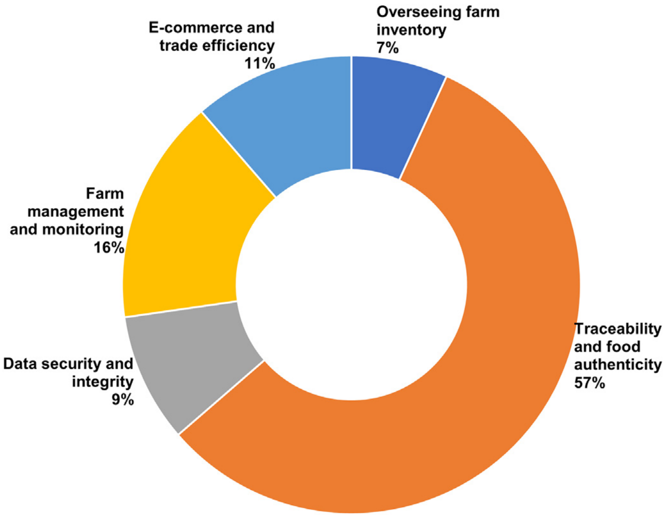

Fig. 4. The distribution of blockchain use cases in agri-food across retrieved articles (total articles: 44).

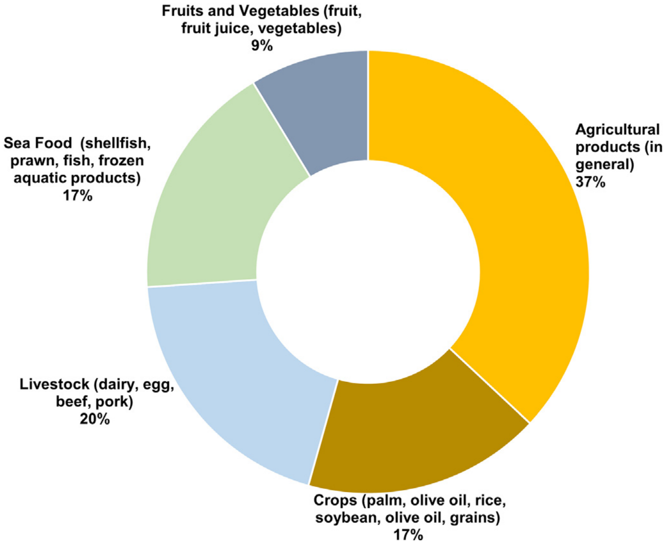

Fig. 5. The distribution of food commodity types in the reviewed blockchain use cases (total articles: 44). Note: in the studies conducted by Köhler and Pizzol (2020) and Li et al. (2020a) more than one target products are included.

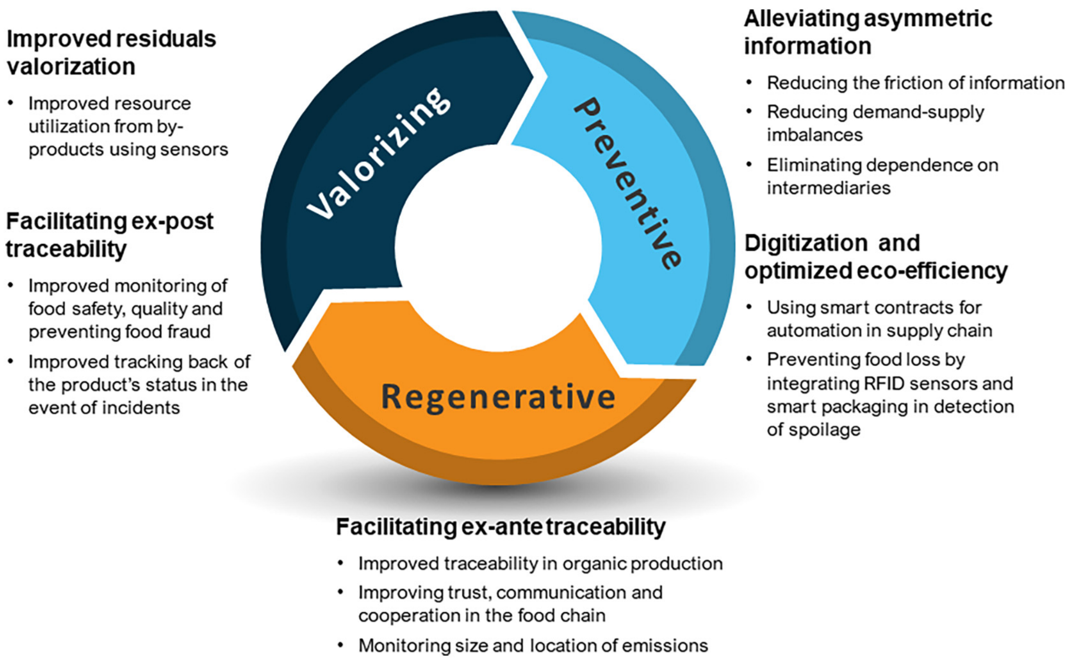

Fig. 6. The potential of blockchain technology in unlashing Circular Economy strategies within the food supply chain. Source: Own elaboration.

in supply and demand. A blockchain system manages data transactions via a distributed system of computing nodes in a peer-to-peer network. The secure and decentralized sharing of data reduces the friction of information exchange and increases transparency (Guido et al., 2020). Zhang et al. (2020a) examined the effectiveness of a blockchain-based information management system for handling crop breeding storage data. The blockchain storage mechanism was devised to ensure an efficient and safe high-throughput breeding data storage solution,

Table 2
Summary of evidence on employing blockchain-based use cases on the 'Circular Economy' within the agri-food domain.

Themes	Contribution to CE (*CE strategy*)[a]	Examples (frequency)[b]	References
Preventing food surplus and loss (Preventive)	Alleviating asymmetric information (*Reduce, Refuse*)	Reducing the friction of information (2)	Chen et al. (2020); Guido et al. (2020)
		Reducing demand-supply imbalances (6)	Kumar et al. (2020); Leng et al. (2018); Liu et al. (2020); Tsolakis et al. (2021); Zhang (2020); Zhang et al. (2020a)
		Eliminating intermediaries that are typically third-party guarantors (5)	Kamble et al. (2020); Köhler and Pizzol (2020); Salah et al. (2019); Syromyatnikov et al. (2020); Tönnissen and Teuteberg (2020)
	Digitization and optimized eco-efficiency (*Reduce, Refuse*)	Using smart contracts for automation in the supply chain and improving eco-efficiency (4)	Hang et al. (2020); Mao et al. (2018); Yu et al. (2020); Zhang et al. (2021)
		Preventing food loss through integration with IoT devices (6)	Alonso et al. (2020); Cao et al. (2021); Feng et al. (2020a); Iqbal and Butt (2020); Kumar and Iyengar (2017); Mondal et al. (2019); Nesarani et al. (2020)
Valorizing food waste and side streams (Valorize)	Improved residuals valorization (*Re-purpose, Recycle*)	Improved resource utilization, from by-products, using sensors (1)	Park and Li (2021)
	Facilitating ex-post traceability (*Recycle, Recover, Re-purpose, Refuse*)	Improved monitoring of food safety, quality, and preventing food fraud (7)	Alonso et al. (2020); Bumblauskas et al. (2020); George et al. (2019); Grecuccio et al. (2020); Rogerson and Parry (2020); Tan et al. (2020); Yang et al. (2021)
		Improved tracking back of the product's status in the event of incidents (5)	Casino et al. (2021); Garrard and Fielke (2020); Salah et al. (2019); Surasak et al. (2019b); Zhang et al. (2020b)
Preserving and rehabilitating resources (Regenerative)	Facilitating ex-ante traceability (*Regenerate*)	Improved traceability in organic production (4)	Chen et al. (2020); Hu et al. (2021); Shih et al. (2019); van Hilten et al. (2020)
		Improving trust, communication, and cooperation in the food chain (4)	Ferdousi et al. (2020); Longo et al. (2020); Tan et al. (2020); Violino et al. (2020)
		Enabling monitoring sustainability, size, and location of emissions (5)	Chen et al. (2020); Köhler and Pizzol (2020); Li et al. (2020a); Malarvizhi (2019); Mao et al. (2018); Park and Li (2021)

Note: The CE examples and aspects are not mutually exclusive. The most relevant aspects that are addressed in each paper are extracted.
[a] Corresponds to the Circular Economy strategies (i.e., Regenerative, Refuse, Reduce, Reuse, *Re*-purpose, Recycle, Recovery, and Remine) indicated in Fig. 1.
[b] Frequency of the CE aspects that were reported in the reviewed articles.

implemented across scattered breeding locations, whilst also creating the possibility of extending the architecture to enhance performance as data volume grows.

Another issue impacting the current agri-food supply chain is the presence of intermediaries and the lack of trust among them (Behnke and Janssen, 2020). The agri-food chain is characterized by a high level of interactions across a network of food-related enterprises, in which its success depends on the quality of information exchange (Minnens et al., 2019; Yang et al., 2021). Therefore, trust is one of the most crucial factors in the creation of partnerships between the diverse actors in the supply chain (Badea et al., 2014). Table 2 summarizes recent research evidence that blockchain significantly reduces the need for intermediaries within the food supply chain (e.g., Kamble et al., 2020; Köhler and Pizzol, 2020; Salah et al., 2019; Syromyatnikov et al., 2020; Tönnissen and Teuteberg, 2020). Syromyatnikov et al. (2020) conducted a survey regarding the supply chain participants' opinions about the challenges that hinder the development of flexible methods used to manage the supply chain in the agriculture business. The results showed that the lack of digital platforms, in addition to weak partnerships among the supply chain actors are the most problematic issues associated with the development of flexible and efficient supply chain management systems. Among its other potential benefits, blockchain eliminates the intermediaries' dependency on the supply chain for verifying the identity of the actors or authenticating the transactions (e.g., Kamble et al., 2020; Syromyatnikov et al., 2020). Sheel and Nath (2019) have also demonstrated that a blockchain system could improve supply chain performance by improving trust (through transparency and reliability), adaptability (the ability of the firm to adapt according to market needs), alignment (the process of the integration of several supply chain members), agility (ability to meet unexpected changes) and ultimately the competitive performance. However, more research is still needed in the case of global logistic chains, where a large number of stakeholders participate with each other across different geographical regions (Chopra et al., 2022; Tönnissen and Teuteberg, 2020).

3.2.2. Optimized eco-efficiency through digitalization

Digitalization and the automation of logistical systems play a significant role in the management of agricultural resources and achieving eco-efficiency (Chauhan, 2020). Eco-efficiency is a management approach emphasizing the creation of more products while using fewer resources and generating less waste (Ehrenfeld, 2005). Eco-efficiency can be achieved through optimizing resource utilization and reducing waste (during production, storage, and delivery). A blockchain with an automated system reduces the probability of human error and improves production efficiency (Kumar and Iyengar, 2017). Blockchain-based digitalization allows for accurate data exchanges and the performance of real-time actions (often through smart contracts) over decentralized networks (Altay et al., 2022). A blockchain-enabled production line could monitor the sources of raw materials to prevent the extraction and overuse of natural resources (Park and Li, 2021). Park and Li (2021) conducted a systematic review and examined case studies on the ability of the blockchain to reshape supply chain management. The authors concluded that this technology could provide a sustainable resource-use rate, increasing eco-efficiency within the supply chain. However, the blockchain itself is just a platform and its integration with other digital tools, such as smart contracts and the Internet of Things (IoT) devices, makes it an effective system for improving food supply chain management (Friedman and Ormiston, 2022; Köhler and Pizzol, 2020). Table 2 summarizes evidence (extracted from 10 papers) of blockchain-based use cases regarding optimized efficiency through smart contracts (Hang et al., 2020; Mao et al., 2018; Park and Li, 2021; Tan and Ngan, 2020; Yu et al., 2020), the prevention of food loss through integration with sensors, and Radio-Frequency Identification (RFID) devices (e.g., Feng et al., 2020a; Mondal et al., 2019; Nesarani et al., 2020).

Smart contracts are the key component of blockchain-based solutions that enable automation (Köhler and Pizzol, 2020; Yu et al., 2020). Smart contracts are predetermined programs within the blockchain that executes certain actions when specific conditions are fulfilled (Swan, 2015). Literature has acknowledged the importance of smart contract automation in the development of efficient blockchain-based supply chain management solutions (Yang et al., 2021; Yu et al., 2020; Zhang et al., 2021). A smart contract with automated execution can be utilized to trigger payments or other procedures along the supply chain when specified terms are met (Swan, 2015). For instance, Yu et al. (2020) proposed a quality monitoring system for fruit juice production by utilizing smart contracts and machine learning. The proposed system includes five smart contracts associated with storage, pasteurization, enzymolysis, the finished product, and quality evaluation. The system deploys these contracts onto the blockchain and publishes the data blocks (Yu et al., 2020). The first four contracts are the response surface models, which provide data records from the production process, while the last component is used to evaluate sample quality after each production stage. By combining the optimization data with on-chain data, the system utilized the auto-execution of smart contracts to attain reliable and effective food quality monitoring (Yu et al., 2020).

Moreover, blockchain provides a platform for integration with other IoT devices and sensors (Altay et al., 2022).The IoT devices transmit real-time data that can be used to optimize the production process, improve the shelf-life, utilize dynamic price adjustments based on sell-by-dates, and, therefore, prevent food waste and loss (Bhat et al., 2022). This is particularly important for the post-harvest handling and the storage of products where the combination of microbial, enzymatic, chemical, physical, and mechanical factors can lead to food spoilage and waste (Gebresenbet and Bosona, 2012). Mondal et al. (2019) developed blockchain architecture enabled by RFID sensors to implement a tamper-proof digital database for food packaging. This model enables the real-time tracking and observation of packaged food items, as well as the consequent detection of targeted product recalls. According to Mondal et al. (2019), the proposed system enables the determination of a food products' exact shelf-life, therefore, leading to a reduction in waste.

During the production process, sensors have also been deployed to identify poor-quality food components (e.g., fat, amino acids, and pigments) and real-time backtracking is being used to detect the root causes regarding the variation in quality. This enables continuous resource optimization across a product’s value chain, resulting in considerable reductions in food waste. For instance, Nesarani et al. (2020) developed a remote monitoring system for optimum rice production by employing sensors on a blockchain network. This monitoring system improved the secure communication of data (such as temperature, humidity, and rainfall), as well as the removal of incorrect data within the blockchain network. Optimized eco-efficiency, using machine learning algorithms, enabling a systematic approach to rice production management (Nesarani et al., 2020). Moreover, technological improvements in the pre-processing, modelling techniques, and the use of chemometrics has enabled food sensors to revolutionize food authenticity and efficiency in areas such as grain quality monitoring, the post-harvest handling of fruits and vegetables, and the detection of contaminants in animals' food and feed (Wang and Paliwal, 2007).

3.2.3. Enhanced valorization of residuals

Given the broad range of food processing industries, and the large number of waste streams that are generated, it is imperative to improve valorization efficiency within the supply chains (Banasik et al., 2017). Current valorization research is focused on the extraction of high-value bioactive compounds (e.g., phenolic compounds, anthocyanins, and organic acids) from agri-food waste and by-products (Socas-Rodríguez et al., 2021). Therefore, innovative recycling technologies, such as membrane-based processes, pulsed electric-assisted, microwave, ultrasound, and subcritical-water extractions, have emerged for the efficient extraction of such biomolecules from the residues (Castro-Muñoz et al., 2022). Recent advancements in the design of portable spectrometers (e.g., near-infrared spectrometric) and Hyperspectral Imaging (HSI) systems (an imaging spectroscopy which enables the visualization of morphological and biochemical information) has increased transparency within different food sectors (Wang and Paliwal, 2007). Furthermore, advancements in 'omics' techniques (genomics, transcriptomics, proteomics, and metabolomics) have enabled the development of 'Foodomics' which allows for generating large-scale molecular-level microbial contamination measurements (Zheng and Chen, 2014). The utilization of such technologies will significantly enhance food safety through the rapid identification of contamination and adulterants throughout the food chain (Sébédio and Malpuech-Brugère, 2021) and, ultimately, reduce food loss. Foodomic techniques increase our understanding of food composition and chemistry at the molecular level, which means that this knowledge can be used in the development of new foods with improved quality and shelf life. The Foodomics effectiveness can be leveraged through machine learning, meaning that the blockchain is able to contribute to this with its ability to store and manage large data. Despite the importance of data generation through methods such as Foodomics, there remains a paucity of evidence on its integration with the blockchain. This review did not provide direct evidence regarding current blockchain use cases concerning the enhanced waste valorization, although, theoretically, it has the potential. For instance, Park and Li (2021) pointed out that blockchain has the potential to monitor resource utilization, preventing the overuse of natural resources.

3.2.4. Enabling ex-post and ex-ante traceability

The Circular Economy emphasizes valorization solutions such as recycling (Teigiserova et al., 2020) and the upcycling of biomass (Bridgens et al., 2018). Valorization usually includes the bioconversion processes of residuals into organic components, utilizing the discarded or semifinished products as raw materials, and the use of residues or by-products from manufacturing procedures. The prime challenges in this paradigmatic shift are regarding the perishable nature of biomaterials, stringent regulations, and the transparency expectations from consumers. Thus, there is a dire need to establish a traceability mechanism in order to retrieve trusted information regarding the biomass added-value products extracted from biomass (Pandey and Singal, 2022; Socas-Rodríguez et al., 2021). This means tracking the origins of recycled materials, as well as the monitoring of food safety along the supply chain (Socas-Rodríguez et al., 2021). The problem of food safety within the supply chain arises from three factors: (1) contamination (toxins, insects, bacteria, and viruses); (2) spoilage (associated with temperature, humidity, and expiration); and (3) compromise (refering to tampering, misrepresentation, and substitution) (Joo and Han, 2021). Due to its importance, different traceability schemes have been introduced to ensure food safety and quality (see Kok et al., 2012 for details on food traceability methods). Effective traceability will be achieved when the products are tracked throughout the entire supply chain and all necessary information becomes accessible.

Hobbs (2004) differentiates two types of traceability functions: (1) ex-post traceback system (reactive functions); and (2) ex-ante quality assurance (proactive functions). The ex-post traceback system provides information regarding the production and processing methods across the food chain in the event of food safety incidents (Hobbs, 2004). Ex-post traceability allows distributors and food authorities to react immediately to potential safety hazards by tracing back the product status from each stage of the supply chain (Matzembacher et al., 2018). Ex-ante quality assurance refers to the proactive provision of product information and the verification of the product credence attributes (such as provenance, on-farm production practices, etc.) to the consumers that the market would otherwise fail to offer (for a review on different traceability concepts see e.g., Olsen and Borit, 2013).

Blockchain technology seems ideally positioned to support both ex-post traceback and ex-ante quality assurance functions within the food supply chain (see Table 2). Across retrieved literature, 12 papers provided evidence for the improved monitoring of food safety, quality, and the prevention of food fraud.

Concerning the ex-post traceability, prior research suggests that blockchain technology can improve the monitoring of food safety, prevent food fraud (e.g., Alonso et al., 2020; Bumblauskas et al., 2020; George et al., 2019; Grecuccio et al., 2020; Rogerson and Parry, 2020; Yang et al., 2021) and can improve the tracking back of the product's status in the event of incidents (e.g., Casino et al., 2021; Garrard and Fielke, 2020; Salah et al., 2019; Surasak et al., 2019a; Zhang et al., 2020b).

Traceability is arguably one of the most important features of blockchain technology (Cao et al., 2021; Rogerson and Parry, 2020; Zhang et al., 2021). The blockchain serves as a trustworthy, third-party, authenticator of transactions. As all the records are stored and updated across the network, the onus of trust shifts from a third-party, simply holding information, to all the network members, therefore, ensuring security and transparency (Schmitz and Leoni, 2019). Blockchain technology also benefits from cryptography algorithms (complex mathematical algorithms), for system security, which protects the system from information tampering (Liang, 2020).

There are various examples of how blockchain-based traceability applications are employed in the food supply chain to eliminate risks (see Feng et al., 2020b; Pearson et al., 2019 for a detailed overview of the technical aspects of blockchain-based food traceability). For example, Yang et al. (2021) developed a traceable blockchain-based system for the storage and querying of product information within the fruits and vegetables supply chain. The authors concluded that the tamper-proofing and decentralization characteristics improved both query efficiency and the security of private information, as well as ensured the authenticity (reliability) of data in fruit-vegetable traceability. Casino et al. (2021) developed a distributed secure architecture for dairy food traceability. The proposed model incorporated smart contracts within a private local blockchain platform, which led to traceability cost savings. Zhang et al. (2021) proposed a blockchain-IoT monitoring system for frozen aquatic products in order to overcome the shortcomings of conventional tracking systems, such as inefficient centralized data management and tampered information. The proposed blockchain-based system improved aquatic food logistics when compared with the traditional system (Zhang et al., 2021).

The development of different emerging disposable sensing technologies, and their integration with blockchain systems, could provide immense potential for monitoring the biological conditions of various food products (Altay et al., 2022). For instance, BlakBear, an electrical sensor technology start-up, is currently designing a low-cost sensor to examine food quality in real-time (Altay et al., 2022; Barandun et al., 2019). Feng et al. (2020a) examined blockchain-based multi-sensor monitoring systems, incorporating Hazard Analysis and Critical Control Points (HACCP), for collecting quality parameters and improving the transparency of shellfish during storage. They found that the blockchain-based systems provide a reliable real-time monitoring of dynamic indicators, which has resulted in the improved quality of frozen shellfish, and has reduced losses. Overall, these cases support the view that the blockchain has a great potential for food safety traceability, however, there remains a paucity of evidence on how this technology contributes to the problem of valorization within food safety. In a rare study, Casado-Vara et al. (2018) proposed a traceability model where, with the use of blockchain technology, consumers can learn about the origin of the product and whether it comes from recycled materials or a fresh source.

In the light of ex-ante traceability, Table 2 summarizes the results from 13 papers indicating the role of blockchain technology in improving the traceability of organic production (see Chen et al., 2020; Hu et al., 2021; Shih et al., 2019; van Hilten et al., 2020). Furthermore, evidence from the literature emphasizes how blockchain technology improves trust in communicated claims (e.g., Ferdousi et al., 2020; Longo et al., 2020; Violino et al., 2020), and the potential regarding the monitoring of sustainability performance within the supply chain (e.g., Malarvizhi, 2019; Mao et al., 2018; Park and Li, 2021).

A decentralized blockchain creates trust at any given point in the supply chain, leading to more effective data management and control (Bumblauskas et al., 2020; Kamath, 2018). This is especially important for tracking the supply chains of organic food. Blockchain technology can be used to indicate the use of pesticides, genetically modified organisms, fair payments, and the environmental or carbon footprint. Chen et al. (2020) examined the concept of '*digital agricultural democratization*' and proposed a blockchain-based electronic agriculture system. This blockchain system automatically collected and loaded data using smart devices, which led to improved organic food tracking.

van Hilten et al. (2020) investigated the role of blockchain technology in organic food traceability. The results of the case studies revealed that blockchain technology enables faster food traceability in light of European regulations. Enhanced risk management, secure data transition, and improved communication accounted for the advantages, however, there are remaining concerns regarding the input validation and the interoperability of blockchain systems (van Hilten et al., 2020).

Previous studies have revealed that consumers rely on both extrinsic and intrinsic quality cues in their purchasing decisions (Grunert, 2005). In the food domain, intrinsic cues are related to the food itself (e.g. safety and quality), whereas extrinsic cues signal to other attributes, such as origin, labelling, altruistic values (e.g., animal welfare, fairness, environmental footprints), and convenience (Grunert, 2005). Therefore, from a consumer perspective, apart from enhancing food safety (Aung and Chang, 2014; Sun and Wang, 2019), traceability systems should also provide information on the extrinsic cues, including the social and environmental impacts of a product, enabling consumers to make more informed purchase decisions (Chopra et al., 2022; Islam and Cullen, 2021; Matzembacher et al., 2018). A blockchain start-up, 'Provenance', would be an example of altruistic traceability. Using a blockchain-based system, Provenance tracks tuna fish, which is caught along the supply chain and authenticates the fish with verified social sustainability claims (including human rights abuses, overfishing, and fraud) (Provenance, 2022). Reviewing the literature also indicates that a blockchain's distributed ledger platform can be used for the recording of information about the location and size of emissions, especially carbon emissions, waste water, or toxic pollutants, from each stage of the supply chain (Park and Li, 2021). This information is essential for a better implementation of regenerative practices.

4. Discussion

This review provides a broad overview of areas where blockchain technology can possibly contribute to achieving CE within the food supply chain. Our review identified two major themes across the retrieved articles discussing blockchain technology for a) accelerating supply chain traceability, and b) preventing food loss/waste. We elaborate on these outcomes in more detail below, followed by the limitations and suggestions for future research.

4.1. Blockchain as a platform to accelerate supply chain traceability

The most obvious finding to emerge from the analysis is that the majority of blockchain technology use cases in the agri-food sector concerns traceability and food supply chain management. Other areas of interest include farm management and trade efficiency. This result corroborates the findings of a great deal of the previous reviews (e.g., Demestichas et al., 2020; Duan et al., 2020; Li et al., 2021; Zhao et al., 2019) indicating the potential of blockchain for improving food traceability.

Recent advancements in agri-food digitalization, through the integration of artificial intelligence, sensors, and simulation modelling, have improved the quality of food traceability. Nevertheless, the effectiveness of current applications regarding the IoT devices and sensors is rather limited in maintaining food safety due to their centralized structure and security issues (Sadique et al., 2018). Blockchain technology is highly appreciated in providing secure traceability data, by using cybersecurity frameworks and assurance mechanisms (e.g., using a decentralized distributed ledger, time stamps, and consensus structures), to reduce the risks from attacks and fraud. Blockchain systems can also incorporate sensors and RFID technologies which promotes accuracy in the monitoring of the products' date and temperature, particularly during cold storage and distribution, consequently contributing to waste mitigation (Ndraha et al., 2018). The current study found that these possibilities improve the blockchain-based ex-post traceability in terms of accountability (e.g., Kshetri, 2018; Tama et al., 2017), fraud prevention (e.g., Jin et al., 2017), and food authentication (e.g., Galvez et al., 2018; Kshetri, 2018). This also corroborates with the results from Li et al. (2021), Dutta et al. (2020) and Pandey et al. (2022).

There is also emerging research that examines the impact of blockchain-based ex-ante traceability, for example, within organic production and regenerative practices (e.g., Chen et al., 2020; van Hilten et al., 2020). In addition, this review identifies the blockchain as a powerful technology that can significantly enhance data transparency and accountability regarding the supply chains' sustainability impact. Providing sustainability performance reports of the supply chain will take a lot of collaboration among data creators and users from various data solutions (Chopra et al., 2022). Blockchain technology can help enterprises present more accurate, reliable, and readily available data on issues, such as carbon emissions and ethical practices. This finding is consistent with previous reviews (e.g., Rana et al., 2021; Schahczenski and Schahczenski, 2020; Tiscini et al., 2020).

4.2. Preventing food loss/waste

One of the main drivers of food loss is the problem of asymmetric information and disparities between supply and demand. This is particularly important in the current COVID-19 post-pandemic period, with the increasing cost of raw materials (Dmytrów et al., 2021; Martínez et al., 2022). In accordance with previous reviews (e.g., Duan et al., 2020; Li et al., 2021), the findings of this paper indicate that the blockchain improves transparency and trust in transactions between enterprises, whilst reducing information asymmetry, and therefore, promoting efficiency.

Due to the multifaceted and complex nature of the food supply chain, a transition towards the CE requires stakeholders to interact effectively along the chain (Aslam et al., 2021). This also requires advanced forecasting methods and efficient systems, for storing, and processing, big (and usually rapidly changing) data that is collected from different platforms (Modgil et al., 2021). Thus, computational intelligence techniques can reduce the need for human intervention, these techniques enable the detection and extraction of known patterns of information, allowing for the optimization of the processes (Haftor et al., 2021; Nedjah et al., 2022).

The findings of this paper indicate that blockchain can help to improve eco-efficiency by providing a platform for production automation, particularly in the early stages of the food supply chain. Digitalization and the obtaining of real-time data across different IoT devices, will optimize resource utilization (Li et al., 2020b). Integrating blockchain systems with RFID and smart packaging technologies improves the efficiency of real-time food stock and delivery management, as well as assists in the identification of where and how the food is going to expire, potentially decreasing food waste. Blockchain integration with other IoT solutions can also potentially help to improve resource utilization in the valorization processes (Teigiserova et al., 2020). Yet, the implementation of solutions for optimizing resource utilization from recycled biomass seems to be underrepresented in the literature.

Another challenge in waste valorization is the problem of food safety, taking into consideration that agricultural commodities are prone to microbial spoilage (Ada et al., 2021; Domínguez-Perles et al., 2018). Thus, the successful valorization of the waste streams and by-products depends, to a great extent, on the traceability and the quality of monitoring within the food production system (van der Goot et al., 2016). Despite its potential, this paper did not provide compelling evidence of current blockchain-based implementations for utilizing waste/by-products and quality monitoring of resulting food ingredients. With today's global supply chain becoming increasingly complex, and due to the perishable nature of agricultural products, it is clear that traceability for recycled materials will undoubtedly need to adapt to these conditions (Socas-Rodríguez et al., 2021).

4.3. Limitations

This study consists of a scoping literature review built on three major scientific databases (Web of Science, Scopus, and ScienceDirect) covering the period 2017–2021. During the course of this study, the researchers did not include additional literature sources, such as FSTA – Food Science and Technology Abstracts, CAB Abstracts, Google Scholar, AgEconSearch and other numerous catalogues of grey literature, technical journals, and non-peer-reviewed articles, which could be beneficial in delivering a more inclusive representation of such a recent topic. However, arguably the literature databases included in the investigation incorporate high-quality, peer-reviewed articles, and this choice enabled the authors to focus on the content rather than on the scientific soundness of the studies examined. Since the focus of this paper was not to provide a critical evaluation of the drivers and challenges regarding the incorporation of blockchain-based solutions, recent reviews authored by Pandey and Singal (2022) and Li et al. (2021) can complement this study.

4.4. Future research

This study provides an overview of the literature on the relevancy of blockchain-based solutions for the CE the food system, which allows the authors to identify research gaps and suggest an agenda for future research directions.

Firstly, the industrial-scale application of blockchain technology is still in its embryonic stage, (Kamble et al., 2019; Queiroz and Fosso Wamba, 2019) with our understanding of CE implications from blockchain-based solutions still limited (Nayal et al., 2021). Based on the available literature, this review identifies four central aspects where blockchain can contribute to the CE transition, (i.e., the possibility to alleviate asymmetric information within the food supply chain, reach optimized eco-efficiency, enable ex-post and ex-ante traceability, and enhance residuals valorization). However, as highlighted by Köhler and Pizzol (2020) blockchain by itself is not an end-to-end solution, but it is rather a tool that can be combined with a multitude of technologies, such as sensor networks and the IoT to provide a long-term impact on the food supply chain sustainability. It is also important to study the internal (e.g., technological competences, managerial concerns, etc.) and the external (e.g., regulations, customer demands, etc.) drivers in adopting blockchain enabled CE implementations (Aibar-Guzmán et al., 2022; Marti and Puertas, 2022; Nayal et al., 2021). Research on how an integrated blockchain throughout the whole food supply chain from farm-to-fork can affect CE performance would be another important research direction.

Secondly, blockchain technology could improve supply chain performance by improving trust, adaptability, alignment, and agility. It has a great potential to improve the traceability and eco-efficiency operations within the food supply chain, which improves the CE status. Yet, there exists many challenges which can hamper blockchain utilization within the food supply chain. Issues, such as the complexity of the design, cost of the implementation, scalability related to performance and computation, as well as the lack of adequate legislation, were identified as future research opportunities (Li et al., 2021; Pandey et al., 2022; Vu et al., 2021).

The current cost estimation for the blockchain technology discussed in the literature considers the computation cost of the blockchain only. The cost of implementation and the transition from a traditional model to the blockchain, as well as integrating that with the other technologies (e.g., IoT), in addition to the costs associated with the maintenance of the blockchain, is not well studied. It is worth mentioning that, in addition to the technical issues mentioned above, acceptance of the blockchain within the community is a great challenge (Nikolaou and Tsagarakis, 2021). The main issue impacting social acceptance of the blockchain is the fact that, although cryptocurrency is using blockchain technology, it is mistakenly assumed to be the same in some communities (Yeoh, 2017).

5. Conclusion

In this paper, after a thorough literature review, the authors first provided a comparison of major use cases that are currently employed in food supply chains and then conducted a synthesis analysis to explore the potential of blockchain technology, utilized as a part of the Circular Economy within the food system. Such a transition requires the prevention of food loss, especially in the early stages of the food supply chain, as well as valorizing waste streams, in addition to the by-products generated through utilization and processing. Our review demonstrated that the use of blockchain technology within the food sector has great potential in, for example, preventing food loss, adopting organic farming practices, maintaining soil health, decreasing environmental impacts, and ensuring biodiversity and the resilience of ecosystem services. In particular, we discussed how blockchain could improve the ex-ante and ex-post traceability in the food supply chains. The ex-ante blockchain traceability enables improving regenerative practices, preserving natural resources, and detecting emissions. The ex-post blockchain traceability enhances the monitoring of food safety and the tracking of the product in the event of incidents. The authors then discussed a blockchain's digitalization operational advantages and how it can help improve optimized eco-efficiency, reducing information asymmetry in food supply chains. Our results indicate that integration with other digital solutions such as the IoT, could help in reducing the supply-demand imbalances and food surplus, thus lowering food loss.

All these factors are important when trying to handle the growing world population, sustainability concerns, and the scarcity of the natural resources present in the agri-food sector, along with the permanent challenges of meeting food security and superior quality standards (safety, environment, welfare, and ethics) while maintaining food affordability. Yet, most of the currently proposed blockchain-based systems did not move beyond the proof-of-concept and conceptual stages, hence, offering little empirical evidence. There is, therefore, a need for further research regarding ways to implement CE systems, using blockchain technology, – especially in global logistic chains, where many stakeholders are involved in different geographical regions.

This paper's findings provide insights that aim to guide the development of more effective blockchain-based supply chain management solutions within the agri-food sector and other sectors. Despite the overwhelming advantages (such as transparency, tamper-resistance, and decentralization), this technology needs to overcome technical hurdles, such as energy consumption and the computation mechanisms needed for the dispersed complex agricultural supply chains.

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Declaration of competing interest

The authors declare no conflict of interest. There's no financial/personal interest or belief that could affect our work. The funder had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results. There is no previous or pending publication of the manuscript's content in any conference proceedings, letters to journals and brief communications, or as pre-prints on repositories like arXiv, biorXiv, Figshare, etc.

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