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Digitalization and Blockchain Integration in Agri-Food Supply Chains: Towards a Resilient, Circular, and Sustainable Future

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Abstract

The agri-food sector is currently undergoing a significant digital transformation, driven by climate change, frequent supply chain disruptions, and increasing demand for transparency and food safety. This article, based on a systematic review of 113 recent studies (in line with the PRISMA guidelines), delves into how emerging digital technologies, particularly blockchain, are reshaping agri-food supply chains towards sustainability, a circular economy, and complete product traceability from production to the final consumer. The paper identifies the main enabling factors, barriers, and implementation models of blockchain and other technologies associated with Industry 4.0 (IoT, artificial intelligence, smart contracts), highlighting their role in increasing the resilience of supply chains, optimising quality control, and sustainable resource management. A key contribution of the study is the introduction of the CTSAF (Converging Technologies for Sustainable Agri-Food Chains) conceptual framework, which provides practical implications for policymakers and organisations, enabling them to make informed decisions. The results also provide valuable insights for future research, supporting the transition to a more transparent, resilient, and sustainable global food system.

Keywords: blockchain; circular economy; traceability; digitization; food safety; food chain

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1. Introduction

In the current context, marked by the intensification of food security issues, the effects of climate change, high levels of food waste, and economic instability, agri-food supply chains are under increasing pressure to strengthen their resilience, improve their transparency, and adopt sustainability-oriented practices [1]. Digitalisation and the integration of emerging technologies, such as blockchain, the Internet of Things (IoT), and artificial intelligence (AI), are considered essential levers for the transformation of the agri-food system, facilitating traceability, efficient data management, and reducing operational risks [2].

Blockchain technology, defined as a shared information system for validating, securing, and permanently storing transactions between multiple parties in a distributed ledger, has numerous applications in the agricultural and food industry [3]. Thus, within the literature, blockchain technology is increasingly approached as an emerging tool with transformative potential on agri-food supply chains, being valued especially for its ability to ensure a higher level of traceability, to strengthen trust and responsibility between the actors involved, as well as to improve the efficiency and transparency of operational processes in the agri-food chain [4]. Blockchain technology enables decentralised, secure, and immutable recording of transactions, which is essential in a sector where food safety and traceability are critical factors for building trust and accountability along the supply chain. The use of blockchain in the agri-food sector enables the strengthening of trust among chain actors, increases in visibility into product flows, and automates processes through smart contracts, thereby reducing errors and administrative costs [5,6]. In addition, the integration of blockchain with IoT and connected sensor systems expands the capacity for real-time monitoring of quality and safety parameters, from production to consumer, and facilitates the implementation of advanced traceability control mechanisms [7]. At the same time, the emergence of new multi-chain models, the utilisation of zero-knowledge proofs, the integration of smart contracts, and the connection with IoT devices indicate a technological maturation that warrants a systematic mapping [8].

Although the transition to Industry 5.0 involves a wide spectrum of emerging technologies, this paper focuses primarily on blockchain. The rationale for this focus is that blockchain functions as an enabling technology; it provides the secure, transparent, and immutable infrastructure upon which other digital solutions, such as IoT, AI, or RFID, can operate effectively. For instance, IoT sensors generate valuable real-time data, but blockchain ensures the trustworthiness and permanence of those records; AI and Big Data analytics can generate powerful insights, yet their relevance depends on the reliability of the underlying information. In this sense, blockchain is not only a digital innovation in its own right, but also a foundation that strengthens the integration of other technologies in agri-food supply chains. By concentrating on blockchain, this study addresses the technology that most directly tackles issues of traceability, trust, and accountability—dimensions that are central to both sustainability goals and Industry 5.0 principles—while still acknowledging the interconnections with other emerging technologies. Beyond economic efficiency, the analysis must include the impact on the triple bottom line (economic performance, social equity, and environmental protection) and the correlation with the objectives of SDG 9 and SDG 12 [2]. However, implementation is frequently limited by the lack of interoperability of standards, high initial investments, digital skills shortages, and regulatory uncertainty [5].

This paper provides a critical and systematic analysis of the recent literature on the application of blockchain and related technologies in agri-food chains, with a focus on the economic and environmental dimensions of sustainability. The study proposes a thematic classification of research directions, identifies existing gaps, and develops an original conceptual framework for understanding the convergence between technology and sustainability in this sector.

1.1. Current Issues and Gaps in Practice

Although the literature reflects a growing interest in the application of blockchain technology in the agri-food sector, the critical analysis of recent studies highlights several conceptual and methodological limitations that hinder an integrated understanding of the potential of this technology in promoting sustainability. Much of the work focuses primarily on traceability and food safety [9–11], largely overlooking the connections between blockchain and circular economy strategies, as well as the long-term economic impact of digitalisation in agri-food chains. The implementation of blockchain technology is often constrained by multiple barriers, among which the technical ones (such as scalability limitations, interoperability difficulties, and privacy challenges), the organisational ones (resistance to change and the shortage of digital skills), and the regulatory ones (lack of a clear and coherent regulatory framework) are distinguished [12]. Emerging technological solutions, such as zero-knowledge proofs mechanisms, optimised Practical Byzantine Fault Tolerance algorithms (e.g., CPBFT), or layer two architectures to improve scalability, can help strengthen data protection and increase processing efficiency; however, these approaches are still insufficiently investigated in the literature [8]. The compatibility of blockchain technology with other emerging technologies, such as IoT, Big Data, and Radio Frequency Identification (RFID), highlights significant potential for integration; however, the lack of a clear and coherent regulatory framework continues to hinder the implementation process [13]. The shortcomings identified include the lack of a holistic framework for assessing impacts (social, economic, political, technological, environmental), the limited research on the effects on post-adoption logistics and operational performance, the absence of uniform methods for quantifying costs and benefits (including socio-environmental costs), and the insufficient studies carried out in developing countries and at the early stages of the chain (agricultural production). More research in these areas could provide valuable insights into the potential impact of blockchain technology in promoting sustainability [12]. There is also a lack of clear strategies to reduce adoption costs and increase the involvement of chain actors, as well as accessible and adaptable digitalisation solutions at all stages of the agri-food supply chain (AFSC) [12].

It is important to stress that this study, while not aiming to address all the gaps previously identified exhaustively, is comprehensive in its analysis. The focus is on specific directions considered a priority in the literature: the contribution of blockchain to promoting responsible consumption, the integration of this technology to achieve the economic and ecological goals of sustainability, as well as the identification of barriers and critical factors influencing its adoption, especially in emerging economies. This comprehensive approach allows the research to directly respond to recurring needs in the current literature, providing an analytical and conceptual perspective that complements existing approaches.

Studies in the literature provide important contributions by highlighting the potential of blockchain for traceability, food safety, and increasing transparency in agri-food chains. However, these studies prove to be limited by the predominant focus on the technical dimension, the absence of holistic approaches to sustainability (economic, ecological, and social), and the lack of unitary conceptual frameworks to correlate the convergence of digitalisation with sustainability objectives. In addition, most studies look at specific cases or pilot projects, without sufficiently addressing the challenges of adoption in emerging economies or the need for standardised cost-benefit assessment methods. These strengths and limitations identified in the literature are the motivation of the present study, which aims to provide a systematic analysis and develop the CTSAF conceptual framework, capable of integrating emerging digital technologies in support of sustainability goals.

1.2. Objectives and Research Questions

The main objective of this study is to carry out a comprehensive and systematic analysis of the application of blockchain technologies and related digital solutions in agri-food chains, in close connection with the economic, ecological, and social dimensions of sustainability. The research aims to move beyond the limited focus on traceability and food safety in the literature, investigating the contribution of blockchain to responsible consumption, its role in integrating economic and environmental goals, as well as the barriers and success factors that condition adoption, especially in emerging economies. In this context, the study proposes a CTSAF (Converging Technologies for Sustainable Agri-Food Chains) conceptual framework, capable of integrating these perspectives and providing a practical tool for decision-makers and organisations in the transition to sustainable and resilient agri-food chains.

To guide the systematic analysis of the literature and logically structure the interpretation of the results, it is necessary to formulate well-defined research questions. These questions are aligned with both the general objectives of the study and the gaps identified in the literature. Our comprehensive literature review ensures that the study's findings are based on a solid foundation of existing knowledge.

RQ1: What Is the Contribution of Blockchain Technologies to Promoting the Circular Economy and Responsible Consumption in the Food Sector?

Initially, blockchain was primarily adopted in the food sector for enhancing traceability and safety [14–16]. However, the current literature points to a significant broadening of its applications towards the circular economy [12]. Circular Economy, understood as a systemic approach that aims to minimise waste and maximise the efficient use of resources through reuse, recycling, and closed-loop systems, provides an essential framework for assessing sustainability in agri-food chains. As per the latest research, blockchain is now being used to bolster traceability and transparency in the food supply chain [17,18], promote resource reuse [19], and mitigate the risk of food fraud [20]. For instance, the study by Kramer et al. (2024) presents cases where consumers are rewarded for making responsible choices through blockchain-based tokenised systems [21]. Furthermore, contract-based solutions are being innovatively used to enhance the resilience, security, and efficiency of data management [22,23]. Therefore, blockchain not only ensures efficiency and traceability but also fosters sustainable consumer behaviours and circular models in the industry.

RQ2: How is blockchain Technology Integrated into Agri-Food Supply Chains to Support Economic and Environmental Sustainability Goals?

The integration of blockchain technology in agri-food supply chains has increased significantly in recent years. This technology plays a crucial role in enhancing traceability and trust among stakeholders, while also supporting sustainability goals. The literature highlights the potential of blockchain technology to contribute to reducing economic losses and strengthening transparent and accountable practices. It does so by establishing mechanisms for the circulation of immutable and verifiable information between farmers, processors, and retailers, which are essential aspects for strengthening the governance and sustainability of agri-food chains [24,25]. For example, research by Tanwar et al. (2022) demonstrated that blockchain, when combined with IoT, can generate significant resource savings and optimise logistics processes from an energy perspective [26]. Moreover, promoting digital traceability in the food industry encourages business innovation, with knowledge management serving as a mediator and dynamic capabilities reinforcing this link, which underscores the need for managers to adapt their strategies in order to fully leverage digital resources and achieve sustainable competitive advantage [27]. From an economic perspective, blockchain technology reduces transactional costs by eliminating intermediaries and optimising data exchange, thereby increasing logistics efficiency and facilitating access to markets for small producers [28]. In addition, by integrating with IoT and sensors, temperature, humidity, or location data is automatically recorded, preventing food loss and waste—both an economic benefit (maximising product value) and an environmental benefit (reducing the carbon footprint associated with waste) [9,29]. Thus, the literature suggests that blockchain acts not only as a data security technology but also as a vector of sustainable transformation in the agri-food sector.

RQ3: What Are the Main Barriers and Success Factors in the Adoption of Blockchain in the Agri-Food sector, Especially in the Context of Emerging Economies?

The adoption of blockchain in the agri-food sector faces several barriers, especially in emerging economies, where access to digital infrastructure, technological literacy, and the lack of clear regulations remain significant challenges. Reviewed studies frequently mention obstacles such as high implementation costs [10,11,24,30], lack of specialised personnel [10,24,31], technological constraints [32], and lack of interoperability between existing systems [11,30]. At the same time, the success of integration is contingent upon factors such as government support [33], the presence of collaborative platforms [34], and the attitude and perception of risk associated with change [35]. For example, in the study by Kramer et al. (2021), it is highlighted that the adoption of blockchain technology in coffee supply chains is significantly influenced by the normative approach in stakeholder management [36], while Oțoiu et al. (2025) show that the adoption of blockchain technology in the food processing and distribution industry is closely related to its integration with other technologies in the food industry [37]. Agriculture 4.0 and 5.0 technologies, including IoT, sensors, AI, Machine Learning (ML), Radio Frequency Identification (RFID), drones, and edge computing (EC), facilitate real-time traceability and monitoring. These factors are essential for understanding the degree of integration and scalability of blockchain solutions in various agri-food fields.

The novelty of this study lies in its integrated approach to the literature on the application of blockchain in agri-food chains, correlating the economic and environmental dimensions with emerging trends in technological convergence. The usefulness of the research lies in both identifying the barriers and opportunities related to implementation and proposing an innovative conceptual framework that can guide future research and support decision-makers in adopting sustainable digital solutions. The structure of the article reflects this dual contribution; after presenting the context and current issues, the research methodology used to substantiate this research is presented. The study continues with a critical analysis of the existing literature that synthesises the main results obtained by specialists in the field and the formulation of the CTSAF model (Converging Technologies for Sustainable Agri-Food Chains). Finally, the theoretical and practical implications are discussed, along with the limitations and future directions of research.

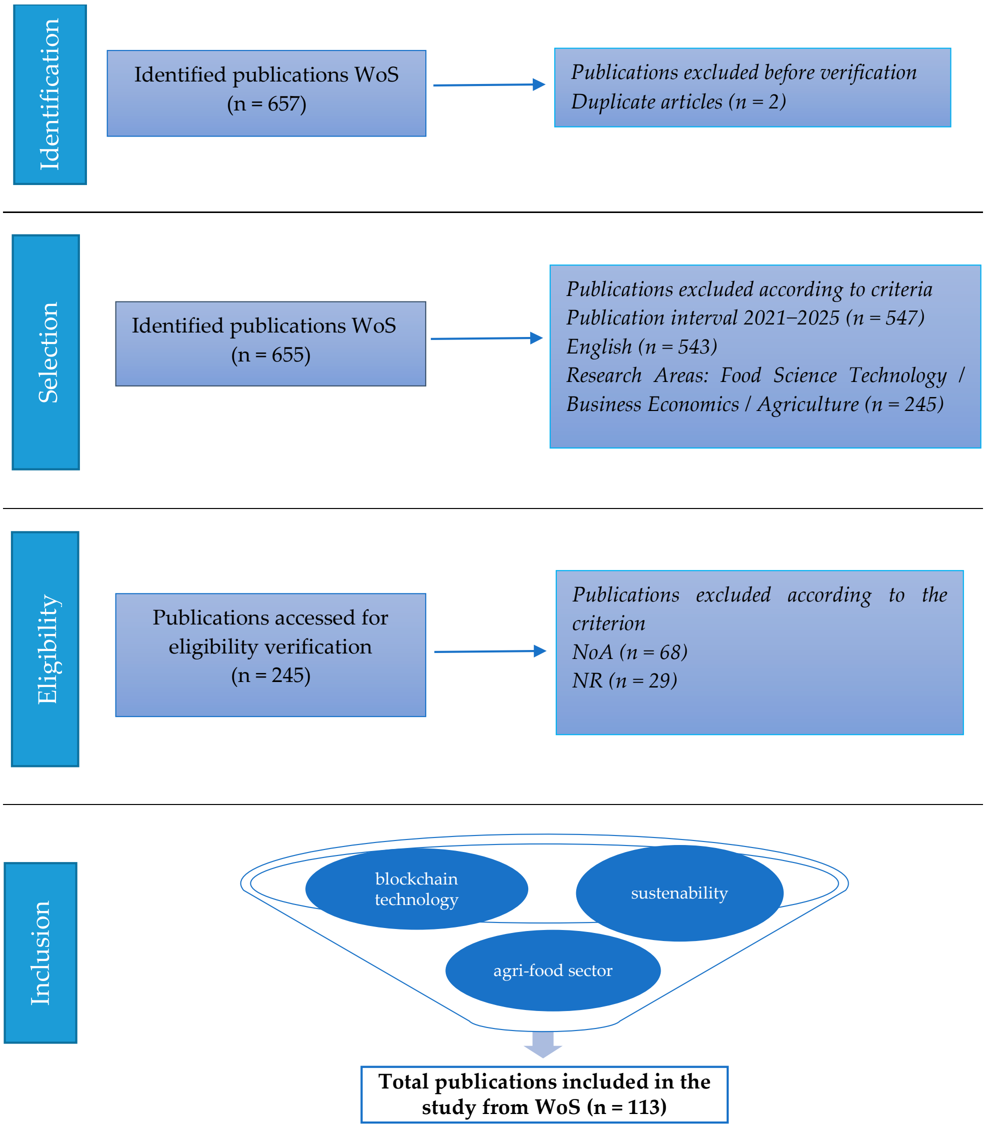
2. Research Design and Methodology

This paper aims to explore the role of emerging technologies, especially blockchain technologies and related digital solutions, in enhancing the sustainability of agri-food chains. To achieve this, a systematic review of the scientific literature was conducted, following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines as shown in (Figure 1). The process was rigorously structured in the following four main stages: identification, selection, eligibility, and inclusion.

The identification stage was meticulously conducted, involving a comprehensive search of the Web of Science Core Collection database using combinations of relevant keywords, such as “blockchain”, “food industry”, “agri-food”, and “sustainability”. The query returned a total of 657 initial results, ensuring a thorough exploration of the available literature.

In the selection phase, a series of rigorous filters were meticulously applied to refine the following results: only articles published between 2021 and 2025, in English, in the fields of “Food Science Technology”, “Business Economics”, and “Agriculture” were selected. This meticulous stage led to the reduction of the corpus to 246 articles, ensuring the highest quality of research.

Subsequently, in the eligibility stage, articles that were not available in Open Access (68 papers) were excluded, as well as those that, after reading the title and abstract, did not directly address topics relevant to the research objectives (29 papers). Following this filtering, 148 articles were selected for complete content analysis.



Note (NoA = no open access; NR = no key terms representing the main subject of the research are found in the abstract)

Wos = Web of Science

Figure 1. Process of identification, selection, eligibility, and inclusion of WoS publications for blockchain analysis in the agri-food sector.

To ensure the robustness of the review, we applied explicit exclusion criteria at each stage, such as lack of open access, insufficient alignment with the research objectives, or absence of references to blockchain and related technologies. Furthermore, a quality assessment was carried out for all eligible studies, based on their relevance to the agri-food sector, the explicit integration of blockchain or converging digital technologies (IoT, AI, ZKP), their practical applicability in agri-food supply chains, and their potential impact on economic and environmental sustainability. This rigorous evaluation process instilled confidence in the robustness of our analysis, leading us to include a total of 113 articles in the final analysis.

In order to ensure the consistency and traceability of the data, each selected article was analysed from the perspective of the following variables: the technology approached, the purpose of the research, the function in the agri-food chain targeted, the proposed solution, the level of technological maturity, the impact on sustainability, the limitations identified, and the relevance for the present study. These elements were presented both in structured form and through discursive comments integrated into the results and discussions section.

To complete the qualitative analysis and identify the thematic interconnections in the literature, a bibliometric mapping was carried out using the VOSviewer version 1.6.20 software. The results of this analysis generated a co-occurrence map of the terms extracted from the selected articles, structured in four major clusters, as shown in (Figure 2).

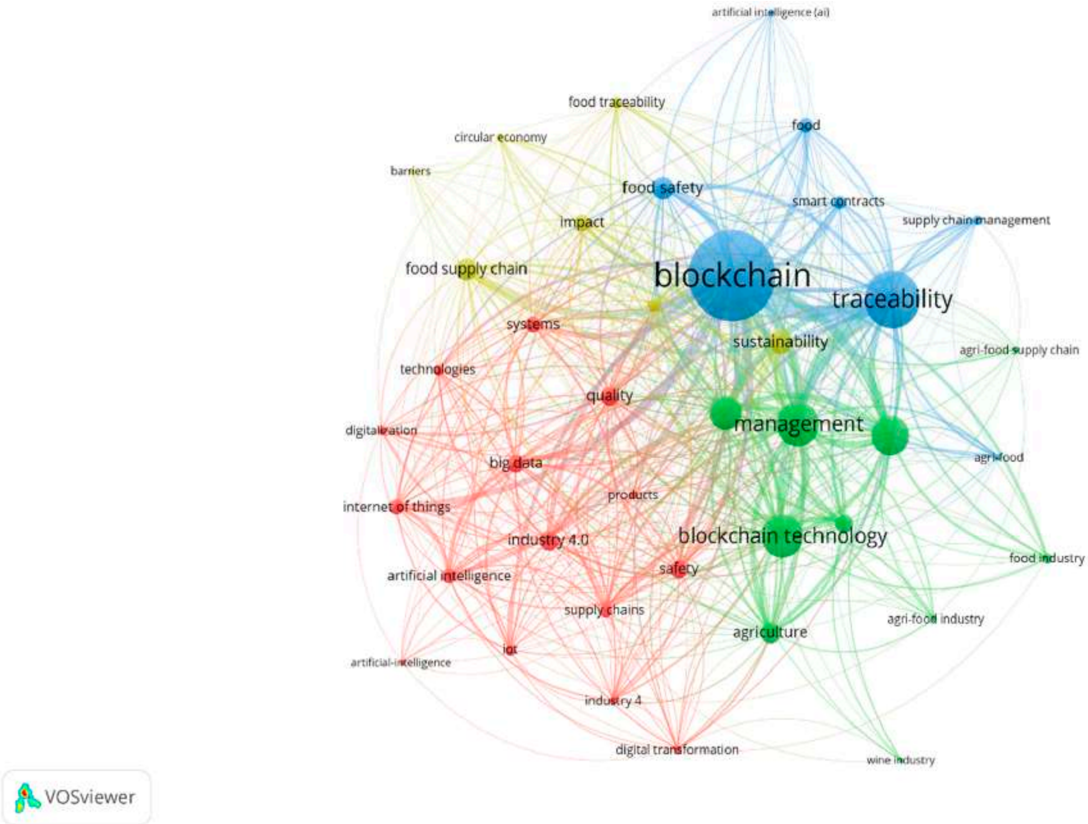


Figure 2. Bibliometric map of keywords.

The red cluster groups concepts associated with emerging technologies and digital infrastructures, such as artificial intelligence, Internet of Things, Big Data, and Industry 4.0, highlighting the role of blockchain as part of a broader technological ecosystem. The green cluster brings together terms related to management, agriculture, sustainability, and supply chains, emphasising the application dimension and the impact on operational efficiency and sustainable performance. The blue cluster is focused on traceability, food safety, and smart contracts, highlighting the function of blockchain to increase transparency and trust in agri-food chains. At the same time, the yellow cluster reflects the themes related to the circular economy, barriers, and impact, suggesting the relevance of blockchain for innovation and sustainable transition strategies. The central positioning of the term "blockchain" confirms its role as a conceptual and technological pivot, connecting these areas in an interdependent network of knowledge, with both theoretical and practical implications.

3. Results

The results obtained are presented and analysed in this section, being structured on subsections corresponding to the research directions identified in WoS, to highlight the identified relationships, interpret the empirical implications, and substantiate the experimental conclusions with theoretical and practical relevance. Through a thematic analysis based on the fields of application of digital technologies identified in the literature, the following four major emerging research directions are outlined: (1) emerging technologies, (2) sustainable management of supply chains, (3) traceability and food safety as central elements of consumer trust, and (4) digital transformation agri-food systems, with an impact on their resilience and competitiveness.

3.1. Emerging Technologies

The integration of blockchain and IoT in agri-food supply chains contributes to strengthening traceability, ensuring distribution consistency, reducing costs, and enhancing operational reliability. These technologies offer a decentralised and secure framework for data management and process automation using smart contracts [7,38,39]. Smart contracts drive transparency, immutability, and security, extending the applications of blockchain beyond traceability to areas such as decentralised finance (DeFi), secure data logging, traceability of agricultural inputs, decentralised agricultural markets, contract farming, government services, and food quality assurance [17]. At the same time, AI and Big Data support the collection, storage, and analysis of large volumes of data from sensors, online databases, genomic data, and social networks, playing a role in the early detection of risks.

At the same time, blockchain complements this framework by ensuring data security and traceability, preventing forgery, and building consumer trust [15]. In addition, the integration of AI with detection methods (spectroscopy, visual imaging, sensors) and with IoT and blockchain provides advanced mechanisms for authenticity and traceability, with real-time monitoring, food fraud detection, and support for the transition to Food Industry 4.0 through automation, predictive analytics, and smart decisions [40]. Technical models based on layered architectures (physical, IoT, and Blockchain) enhance smart data collection, full traceability, and resistance to manipulation by implementing information nodes and smart contracts for production, processing, distribution, sales, and surveillance entities [41].

To overcome the current limitations, multi-chain architectures with zero-knowledge proofs, hierarchical encryption, and consensus-optimised mechanisms are proposed [8], as well as cross-chain models based on smart contracts and consensus Supervision Practical Byzantine Fault Tolerance (SPBFT), which reduce latency and costs [22,23]. In agri-food critical infrastructures, blockchain is being investigated for data authentication and validation, access security, attack detection and attribution, data protection, and recovery, which have direct implications for traceability and logistics [42]. The convergence of blockchain with Industry 4.0 and Web 3.0 tools (IoT, RFID, Cloud Computing, GPS, Big Data analytics, and AI) allows the development of interoperable systems that automatically collect and verify data, optimise logistics, and reduce the risk of food fraud [7,38,39,43]. The digital transformation, accelerated by the COVID-19 pandemic, has strengthened the quality, safety, traceability, and resilience of supply chains, despite barriers such as infrastructure, costs, digital skills, and data governance [2,10]. At the strategic level, the transition to Food Industry 5.0, a concept that emphasises a human-centric, sustainable, and resilient approach to food production and distribution, is supported by conversational/regenerative AI, the Internet of Everything, nano sensors, 4D/5D printing, robots and drones, edge computing, "draftable" blockchain, Metaverse, digital twins, and 6G communications [44,45]. Globally, food security can be improved using emerging technologies, such as IoT, AI, Big Data, blockchain, and robotics. They contribute to ensuring food availability, access, use, stability, agency, and sustainability through solutions for precision agriculture, vertical farming, and aquaponics, as well as traceability based on blockchain and predictive analytics, which helps reduce waste and create automated quality control systems [45].

Reducing food loss and waste relies on IoT (freshness/condition monitoring), AI (demand forecasting, quality assessment), Big Data (price/inventory optimisation), blockchain (transparency, anti-fraud), nanotechnologies and smart packaging (shelf-life extension, tampering detection), 3D printing (by-product capitalisation/customisation)—with persistent investment, training, and public policy needs to overcome costs, skills gaps, legislative barriers, and consumer reluctance [46,47].

The Food Sustainability 4.0 concept integrates AI, IoT, blockchain, smart sensors, robotics, Big Data, and 3D printing to maximise efficiency, traceability, and resilience, reducing waste, carbon footprint, and resources consumed, in line with the logic of the circular economy [45]. In the field of quality, the transition from Food Quality 1.0 to 4.0 incorporates AI, Big Data, digital twins, smart sensors, and blockchain for predicting quality losses, optimising production, and real-time monitoring. However, it requires investments, infrastructure, skills, and security frameworks [48]. Applied studies confirm the quantifiable benefits of these technologies, such as reducing the time to identify the source of contamination from seven days to 2.2 s (Walmart–IBM), 30% decreases in perishables losses through IoT, and reducing grain losses by 20% through digital twins [49]. Other applications include reducing energy consumption by 19–41% in smart greenhouses integrated with blockchain and fuzzy control. Here, blockchain is used for data management and security. At the same time, fuzzy control optimises energy use by adjusting greenhouse conditions based on real-time data [50], as well as generating transparent digital certificates for sustainability [51].

In specific sectors, blockchain + IoT improves traceability and transparency in the food industry [52], AI + IoT + blockchain solutions intervene in all stages of the aviation food safety flow [16], and in the dairy and wine industry, traceability through blockchain and tokenisation is being explored. This involves using blockchain to create a digital representation of physical assets (tokens) that can be traded or used as a form of ownership, thereby enhancing traceability and transparency in these industries [21,53].

The literature review highlights a considerable variety of applications and technology models from the use of smart contracts and multi-chain architectures to integrated IoT–AI–blockchain solutions. However, most of the identified contributions are characterised by a fragmented and predominantly technological approach, while empirical validation in real-world agri-food contexts remains limited. Models such as SPBFT or zero-knowledge proofs offer promising theoretical solutions for overcoming current performance constraints. However, their practical applicability is still limited, raising issues related to scalability, interoperability and governance. At the same time, the focus on technical efficiency frequently diminishes the integration of essential dimensions of sustainability, such as the inclusion of actors, economic accessibility or socio-environmental implications. As a result, the current literature, although rich in technological innovations, fails to provide an integrated view of how these solutions can concretely contribute to increasing the resilience, transparency and sustainability of agri-food chains.

3.2. Sustainable Supply Chain Management

The literature highlights the current limited adoption of blockchain in the agri-food industry, a landscape marked by significant challenges. Notably, Panghal et al. (2023) unearthed the potential of blockchain in reverse logistics within the food processing industry, showcasing its benefits in product authentication, fraud prevention, waste reduction, and returns optimisation [54]. However, they also highlighted the challenges of resource allocation, capital investment, security, and partner coordination. Similarly, Singh and Sharma (2023) demonstrated how blockchain, particularly when integrated with IoT, can bolster transparency and consumer trust, but they also highlighted the scalability and standardisation challenges, especially for SMEs [18]. In a broader context, Krzyzanowski et al. (2021) observed that most blockchain implementations in the agri-food sector are still in the pilot phase, hindered by legislative uncertainties, high costs, and a lack of infrastructure, particularly for small producers [55]. From a systemic viewpoint, Astuti and Hidayati (2023) confirmed that while blockchain can modernise and secure traceability in food chains, its implementation is constrained by high costs, expertise shortages, and regulatory barriers [56].

In addition, Vu et al. (2023) proposed an evidence-based model, structured around the initiation, adoption, and implementation stages, identifying four categories of critical determinants (technological, organisational, environmental, and managerial) for the success of blockchain adoption in food supply chains [57]. Smart contracts represent one of the significant directions for applying blockchain in the agri-food industry. Peng et al. (2023) [5] conducted a bibliometric and content analysis, identifying the following four areas of use: data storage, information management, traceability, and confirmation of rights. The authors proposed the following five-step implementation framework: (1) information flow analysis; (2) smart model design; (3) the selection of technologies (consensus mechanisms, storage and encryption methods, multi-layer architectures); (4) choice of platform (e.g., Ethereum or Hyperledger); and (5) testing and application of the solution) and highlighted current limitations, including smart contract vulnerabilities and high energy consumption [5]. In the same vein, Xue and Li (2023) developed an optimised multi-chain traceability model based on Hyperledger Fabric and Kafka for load balancing, demonstrating significant performance improvements [34]. Song et al. (2023) validated, through a case study applied to the Xinjiang data chain, a blockchain model that reduces latency and optimises storage costs, preserving transparency and protecting private data [28]. In addition, Zhang et al. (2022) proposed an innovative multi-criteria approach for prioritising critical success factors in the implementation of blockchain in sustainable chains, using advanced fuzzy methods (q-ROFS, MULTIMOORA) [58].

Industry studies underscore the significant potential of blockchain to enhance sustainability and traceability in the agri-food industry. Safeer and Pulvento (2024) proposed a model based on blockchain and smart contracts for the Italian tomato industry, aiming to achieve transparency and reduce intermediaries [59]. Ali et al. (2021) built a sustainable framework for the Malaysian food chain, identifying five dimensions of challenges and highlighting the role of regulators [13]. Mangla et al. (2022) analysed the integration of blockchain into the tea supply chain, identifying critical barriers through the SF–AHP method [60]. Manteghi et al. (2023) explored the impact of technology on competitiveness and sustainability in conventional and organic production, demonstrating that organic production is more economically and environmentally sustainable than conventional production [61]. In the extensive beef industry, Cordero–Gutiérrez et al. (2025) have demonstrated that blockchain, integrated with QR codes, can increase the transparency of ecosystem services and the willingness of consumers to pay a premium price [62]. In aquaculture, Chandran et al. (2025) demonstrated that integrating IoT, AI, and blockchain reduces fish mortality and optimises the feed conversion ratio within a scalable and sustainable framework [63].

From a consumer-facing perspective, Panghal et al. (2024) identified five main factors (reliability, sustainability, health impact, trust, and purchase intent) that influence the acceptance of blockchain in sustainable food systems [64]. Gerasimova (2024) has demonstrated that integrating Service Design with blockchain can support consumer engagement and end-to-end traceability, thereby enhancing the circular economy [65]. In Nigeria, Akinbamini et al. (2025) confirmed, through a survey, positive correlations between blockchain, IoT, cloud, ERP, and AI in terms of transparency and collaboration, but highlighted infrastructure and regulatory barriers [66]. Similarly, Cordero–Gutiérrez et al. (2025) demonstrated that blockchain can enhance consumer trust in sustainable products by providing transparent labelling [62].

Blockchain is also being investigated as a tool to support the achievement of the SDGs. A study conducted in the Thai fishing industry identified four key principles for implementing blockchain, demonstrating its potential for enhancing traceability and sustainability [67]. In addition, Hassoun et al. (2022a, 2022b) highlighted how green and digital technologies, including blockchain, can accelerate the transition to sustainable and circular food systems, with benefits in terms of safety, quality, and waste reduction [68,69]. This potential offers hope for a more sustainable and efficient future for the agricultural and food industries.

Bibliometric analyses confirm the exponential growth of scientific interest in blockchain and agri-food sustainability. Ayan et al. (2022) showed that the literature on blockchain in sustainable chains increased by more than 150% annually between 2017 and 2022, highlighting topics such as traceability, circular economy, and resilience [70]. Abbasov and Gurbanzade (2025) identified four evolutionary stages of research in the field and five major thematic clusters, highlighting the increasing integration of digital technologies and the circular economy after 2016 [71]. Morella et al. (2021) systematised the literature on Industry 4.0 in agri-food chains, identifying key performance indicators, the most important of which are sustainability, eco-efficiency, performance, and reliability, and correlating them with technical, educational, and governmental challenges [72].

Recent research also proposes decision-making frameworks for integrating blockchain in agri-food chains. Çolak and Kağnıcıoğlu (2022) developed a comprehensive model for the determinants of blockchain adoption in the supply chain, including technological factors (relative advantage, complexity, compatibility, cost, transparency), organisational (technological readiness), inter-firm (trust and power between partners), and external factors (perceived risk and competitive pressure) [32]. Shahzad et al. (2024) developed an STO (strategic-tactical-operational) framework for cross-industry blockchain integration, as demonstrated through case studies and an implementation in the forest industry [73]. The results show a significant reduction in product origin tracking times (e.g., from seven days to 2.2 s in the case of Walmart), the prevention of fraud and the use of materials from unethical sources, the optimisation of processes, and the creation of business models based on distributed trust [73].

Sharma et al. (2024) proposed a risk assessment methodology based on Venture Preference Rating (VPR) and Strategic Preference Ratings (SPR), applied to food chains in India, identifying strategic priorities to reduce uncertainties and increase transparency (ensuring the stability and clarity of financial terms and strengthening product quality control and transparency) [74]. Jraisat et al. (2023) demonstrate that integrating blockchain into reverse supply networks enhances traceability, transparency, and collaboration, with direct impacts on sustainability and practical management [75]. Giannini et al. (2025) point out that the European Union has recognised the need to strengthen the development and uptake of advanced digital technologies, such as blockchain, to protect the competitiveness and future growth of Member States [76]. In Italy, blockchain is considered a promising solution for supply chain traceability in the agri-food sector; however, empirical evidence on its adoption is limited [76]. Konfo et al. (2023) provide a comprehensive synthesis of recent advances in the use of digital technologies in agri-food processing, highlighting the critical role of IoT, AI, blockchain, Big Data, robotics, and smart sensors in increasing the efficiency, traceability, and sustainability of supply chains [77]. The study presents concrete results from case studies, such as IBM Food Trust and Blue River Technology, which demonstrate significant improvements in food safety, reductions in losses, and optimisation of resource use.

The literature confirms that blockchain has considerable potential to contribute to the sustainability of agri-food chains, but the reported results are uneven and fragmented. A significant part of the studies remains focused on the concept phase or local experiments, which limits the generalisation of the conclusions. In particular, there is a tension between promises of transparency and traceability and the practical realities of costs, organisational integration, and coordination of chain partners. Moreover, the focus is often on technological advantages, while key aspects of sustainable management–such as fair value distribution, the adaptability of SMEs, the involvement of actors in emerging economies, and the institutional capacity to support change–are insufficiently analysed. Even if theoretical and bibliometric models signal a rapid increase in interest and identify critical success factors, there is still a lack of an integrated approach that connects technological performance with the social and ecological objectives of agri-food chains.

3.3. Traceability and Food Safety

The adoption of blockchain in food supply chains is correlated with increased consumer trust and satisfaction [6] demonstrates that integrating this technology in restaurants increases the traceability and perceived safety of food, with the effects being more pronounced in casual restaurants and tourist areas, where blockchain serves as a signal of commitment to transparency and quality. In a broader perspective, Singh and Sharma (2023) highlight that blockchain is a powerful tool to combat food fraud and the erosion of consumer trust through an immutable and transparent traceability system, exemplified by the collaboration of IBM and Walmart, which reduced the time to identify the origin of products from six days to 2.2 s [18]. Similarly, Verna et al. (2025) demonstrate that blockchain, integrated with IoT and RFID, enhances the reliability of digital traceability, fostering trust among actors, while also presenting challenges related to resistance to change and high costs [78].

Studies by Sri Vigna Hema and Manickavasagan (2024) and Yu et al. (2024) confirm this direction, highlighting that blockchain, combined with sensors and electronic tags (RFID, QR, NFC), ensures full traceability and real-time monitoring, reducing the risk of fraud [79,80]. At the same time, Liu et al. (2025) explain, through the theory of trust transfer, how blockchain increases the credibility of information and, implicitly, the intention to buy “green” agricultural products [81]. Complementary contributions are made by Rao et al. (2023) and Shew et al. (2022), who demonstrate that blockchain-based traceability significantly influences consumers’ willingness to pay a premium price, even if traditional certifications (e.g., USDA) continue to hold a higher value [3,82]. Numerous studies confirm the potential of blockchain in preventing and combating food fraud. Duan et al. (2024) demonstrate that blockchain, due to its decentralised and immutable characteristics, provides a robust technological framework for enhancing traceability, authenticity, and transparency in food supply chains [14]. Saha et al. (2024) complement this analysis, identifying eight critical factors (data security, secure collaboration, immutable ledger, etc.) that enhance consumer safety and trust [20].

Multiple dimensions influence the adoption of blockchain in agri-food chains. Mohammed et al. (2023) emphasise the role of technological (compatibility, complexity, cost), organisational (firm size, level of knowledge), and environmental (government support, competitive pressure) factors [83]. Yogarajan et al. (2023), through a systematic review, identifies the following eight primary research directions on the effects of blockchain technology adoption in the agri-food supply chain: factors influencing adoption, impact generated, quantification methods, trade-offs involved, use of complementary digital technologies, solutions to mitigate challenges, contribution to the achievement of the Sustainable Development Goals (SDGs), and emerging themes from domain [12]. Oțoiu et al. (2025) show that the adoption of blockchain technology in the food processing and distribution industry is closely linked to its integration with other technologies in Agriculture 4.0 and 5.0, such as IoT, sensors, AI, machine learning, RFID, drones, or edge computing, which facilitate real-time traceability and monitoring [37].

At the structural level, Kumar et al. (2022) identify 13 critical barriers (lack of resources, lack of public awareness, lack of trust and confidentiality, high investment costs, lack of government regulations, high time to complete transactions, lack of industry standards, lack of IT infrastructure, lack of data regulations, low attitude towards adoption, lack of a consensus protocol, low competence of workers and lack of scalability and interoperability) for blockchain and IoT integration, including lack of regulations and skills shortages, validated through Interpretive Structural Modeling (ISM) and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) [30]. In addition, Sharma et al. (2023) demonstrate that infrastructure, interoperability, and data sovereignty are the primary causal factors in adoption, directly influencing transparency and operational responsiveness [84].

Industry studies highlight the diversified applicability of blockchain. Arvana et al. (2023) demonstrate the benefits of implementing blockchain (Hyperledger Fabric) in the traceability of Portuguese ham, ensuring quick access to information and preventing data omission [85]. Kramer et al. (2021) demonstrate that adoption in coffee chains is influenced by stakeholder management, with social factors and corporate governance shaping attitudes towards technology [36]. Gondal et al. (2023) propose integrating blockchain with IoT smart containers for strawberry transport, which optimises safety and efficiency [9]. In Italy, Silvestri et al. (2025) show that blockchain not only improves traceability but also enhances relationships in agri-food chains (wine, beer, dairy), increasing trust and contractual efficiency [86].

Several studies propose systematic evaluation frameworks and syntheses. Lv et al. (2023) [87] and Menon and Jain (2021) [88] provide a comprehensive review of the literature on traceability, identifying key attributes (immutability, auditability, provenance) and applications in agri-food chains (traceability of fish to prevent illegal fishing and guarantee freshness, monitoring of fruits to avoid contamination and ensure quality, management of data to vegetables through hybrid systems “database + blockchain” for security and transparency, and farm-to-consumer tracing of eggs to provide reliable and complete product information). Pang et al. (2024) propose an assessment framework for bulk product traceability, looking at standardisation and interoperability issues [89]. Rossi et al. (2025) developed a two-dimensional taxonomy for classifying traceability solutions, integrating digital and analytical technologies (AI, IoT, and OMIC) [90]. Peres et al. (2025) propose the Food Quality Management 4.0 framework, demonstrating that blockchain is predominantly used for quality control and assurance, but less so for strategic and innovative functions [24].

Blockchain is becoming an integral part of the agri-food digital ecosystem, with innovative applications. Cornea (2022) proposes the use of blockchain for the digital management of product recalls, reducing notification delays and providing consumers with quick access to information through digital codes [19]. Shahzad et al. (2023) demonstrate that blockchain-based traceability enhances user trust in mobile food delivery apps, thereby strengthening their loyalty [91]. Rajput et al. (2025) highlight the role of blockchain in supporting the circular economy and sustainability by ensuring traceability and transparency along the supply chain, reducing waste through real-time monitoring, increasing operational efficiency through smart contracts, and building consumer trust through access to verified information about the origin and impact of products [92], while Collart and Canales (2021) investigates the potential impact of the widespread adoption of blockchain-based traceability on the U.S. fresh produce supply chain, focusing on challenges such as food safety, food fraud, food loss and waste, as well as the need for more efficient traceability systems [11].

Blockchain has the potential to revolutionise how consumers perceive the safety and quality of agri-food products. However, the relationship between digital traceability and trust is more complex than initial studies suggest. While flagship projects such as IBM–Walmart have demonstrated spectacular performance in reducing the time to identify sources of contamination, there is little evidence that such results can be widely replicated in sectors with limited infrastructure or emerging economies. In addition, research tends to equate technical traceability with food safety, without sufficiently analysing the role of other factors, such as regulations, governance practices or consumer education. Also, the willingness of some consumers to pay a premium price for products certified through blockchain suggests added market value but also raises questions about fairness and accessibility for vulnerable categories. Thus, despite technological advancements, the adoption of blockchain in the field of traceability and food safety remains conditioned by socio-economic, cultural, and institutional factors.

3.4. Digital Transformation

The role of blockchain in the digitalisation of agri-food and sustainability is a key focus of research. Hassoun et al. (2022) demonstrate that integrating blockchain with other Industry 4.0 technologies can accelerate the transition to circular food systems, particularly in the context of plant-based diets [93]. Trevisan and Formentini (2024) confirm the role of digitalisation in reducing food waste, emphasising the importance of interorganizational collaboration and governance [29]. Rao et al. (2022), however, highlight the significant gaps in the Indian industry, where traceability relies almost exclusively on barcodes used for pricing, without a real integration of modern technologies [31].

Blockchain is increasingly being analysed as a marketing and brand management tool. Bartoli et al. (2025) propose the blockchain branding model, through which technology accelerates brand activation, strengthens brand identity, and enhances the brand–consumer relationship by emphasising values such as transparency and authenticity [94]. Similarly, Cao et al. (2021) confirm that blockchain, combined with visual storytelling, can shape consumer perceptions, even if the effects on payment availability remain ambivalent [95].

Technological, organisational, and environmental factors condition the adoption of blockchain. Jahanbin et al. (2023) propose the 3ICT framework, which integrates traceability, transparency, and immutability, tailored to the competences of organisations [96]. George and Al-Ansari (2023) introduce GM-Ledger for authenticating food certificates in international trade, reducing fraud and costs [97]. Vern et al. (2025) provide a traceability framework applicable to agri-food chains by mapping the entire supply chain, defining key processes and data, integrating digital technologies, and establishing the responsibilities of key actors to ensure transparency and control [98]. Compagnucci et al. (2022) use Actor-Network theory to analyse the "trusty" platform, highlighting the role of focal actors and interdisciplinary collaboration [99].

Callinan et al. (2022) apply the extended Technology–Organisation–Environment (TOE) framework, incorporating individual and task-related dimensions, in the fishing industry [33]. They identify resources as the primary enabler and integration as a significant barrier. Treiblmaier et al. (2021) differentiate adoption strategies between established companies and start-ups, emphasising that a lack of understanding of the benefits remains the main barrier [100]. Integrating blockchain with advanced solutions brings significant technical improvements. Guo et al. (2023) propose a dual-layer indexing structure that speeds up traceability queries by up to 8 times [101]. Peng et al. (2022) developed a multi-blockchain rice refined supervision model (MBRRSM), which optimises security, consensus, and storage, demonstrating resilience to cyberattacks [23]. In Greece, Kechagias et al. (2023) are testing an Ethereum application for olive traceability, reducing the time to identify a batch from 45 min to less than a minute and increasing data accuracy by 67% [102]. Zhang et al. (2022) apply blockchain to fresh fruit chains, integrating IoT and cold logistics for real-time monitoring and financial optimisation [103].

In the context of eco-friendly products, Georgescu et al. (2022) show that the positive perception of blockchain is influenced by the safety of origin, perceived utility, and familiarity with the technology, confirming its potential in supporting the 'Farm to Fork' strategy [104]. In addition, Li et al. (2025) integrate the Technology Acceptance Model (TAM) and Technology Readiness Model (TRM) to explain the adoption of blockchain-based traceability, demonstrating that perceived ease and utility, along with technological optimism, significantly influence use intent [105].

In online commerce, Tao and Chao (2024) confirm that blockchain increases in the purchase intention of organic products through transparency and environmental information [106]. Meanwhile, Zhai et al. (2023) highlight that Chinese consumers most value information on pesticide testing and quality certifications in the case of fresh fruits [35].

Exploratory studies bring additional perspectives such as: Cao et al. (2021) show that video storytelling applied to blockchain-certified products can increase trust in labelling but does not guarantee greater willingness to pay a premium price [95]; and Li et al. (2025) confirm that positive attitude and perception of utility are driving adoption, especially for consumers in urban areas [105]. Critical issues in dairy supply chains, such as a lack of transparency, contamination, and adulteration, can be alleviated by implementing blockchain Technology. Khanna et al. (2022) propose a blockchain-based platform for the Indian dairy industry, integrating smart contracts, IoT, and QR codes, which address both social and economic dimensions, as well as operational and sustainability aspects [107]. The results highlight the ability of this architecture to prevent counterfeit products, quickly detect contamination, and reduce food waste by optimising production. From a broader perspective, David et al. (2022) demonstrate, through an empirical study of managers in the Indian food industry, that traceability and distribution integrity are perceived as the primary benefits of blockchain [108]. However, a lack of knowledge, high costs, and technical complexity constitute significant barriers.

In the context of the processed products industry, Vern et al. (2024) show that blockchain strengthens consumer trust through the following four key factors: food authenticity, environmental sustainability, traceability, and transparency [109]. The results suggest that authenticity remains the primary determinant of trust, followed by sustainability and transparency, confirming the relevance of digital technologies in enhancing the competitiveness of the industry. Blockchain's role in enhancing consumer trust is significant, as it can help mitigate the significant risk of food fraud, driven by economic motivations and the difficulty of early detection. Ma et al. (2025) model the competition between ethical and unethical firms, showing that blockchain can function as a reputation protection mechanism for fair firms, stimulating quality improvement and demand consolidation, but with limited effects on the immediate elimination of fraudulent practices [110]. In Turkey, [1] confirms, through a systems dynamics model, the societal impact of blockchain in milk supply chains, where the complete traceability of animal health, milk quality, and distribution processes leads to reduced fraud, an increase in animal welfare, and rural development.

The literature confirms the relevance of digital transformation in the agri-food sector but also highlights a number of limitations. Terrizzi et al. (2024) show that blockchain applications have mainly focused on sustainability, traceability and logistics, but the lack of standards and high costs constitute significant obstacles to their expansion [111]. In a complementary direction, El Jaouhari et al. (2024) propose the integration of the metaverse with blockchain, artificial intelligence, IoT and 5G to strengthen the security of agri-food chains, but highlight the existence of technological, legal and managerial barriers that affect the feasibility of large-scale implementation [112]. An applied contribution is made by Esfandiari (2022), who shows that blockchain can increase efficiency and food safety in the Mexican industry, although the specificity of the context reduces the generalisability of the results [113]. From a conceptual perspective, Hassoun (2025) introduces the notion of "Food Sustainability 4.0", an integrative framework of Industry 4.0 technologies that promises to reduce food waste and promote the circular economy, but the extent of this integration raises challenges related to costs and interoperability [114]. In the same vein, Pavón Losada et al. (2025) analyse business models in the packaging industry and identify the "Safe and Sustainable by Design" approach as the most promising, although its implementation depends on regulatory harmonisation and substantial investments in infrastructure and innovation [115]. These contributions highlight the potential of digital transformation to profoundly reshape agri-food chains, but also the fact that the materialisation of this potential is conditioned by economic, institutional, and technological constraints that are still difficult to overcome. The integration of blockchain with other digital tools (AI, IoT, metaverse, digital twins) is often discussed in promising terms. However, it lacks the standards, infrastructure, and governance frameworks necessary for a coherent implementation. Thus, a discrepancy is emerging between the rhetoric of innovation and the reality of implementation, which suggests that the potential of blockchain in the digital transformation of agri-food systems cannot be evaluated only in terms of technical performance, but requires a critical analysis of the organisational, institutional, and socio-economic conditions that make it possible to scale and sustain solutions.

Overall, the findings highlight the role of blockchain in strengthening transparency and trust, but also reveal the need for an integrative approach, through which the convergence of digital technologies is analysed as a determinant of the sustainability of agri-food chains.

4. Discussion

After a meticulous review of the literature and the synthesis of the 113 articles included in this study, we introduce a ground-breaking conceptual framework, the CTSAF model (Converging Technologies for Sustainable Agri-Food Chains). This model is a pioneering attempt to integrate and structure the convergence of emerging digital technologies–such as blockchain, Internet of Things (IoT), AI, zero-knowledge proofs (ZKP), and smart contracts–in agri-food supply chains, from the perspective of the following three fundamental dimensions of sustainability: economic, ecological, and social. The significance of the CTSAF model lies in its potential to revolutionise the agri-food sector by providing a comprehensive and systematic approach to digital transformation, thereby enhancing sustainability and efficiency.

The CTSAF model is not just a theoretical construct, but a practical tool that can guide the digital transformation of the agri-food sector. The model is based on the idea that digital transformation in the agri-food sector cannot be analysed in isolation on the vertical of a single technology or functionality, but must be understood as a systemic process, in which multiple technologies interact to respond to the specific challenges of each segment of the value chain–from production and processing, to distribution, consumption and reuse. The model proposes a multidimensional mapping, in which technologies are correlated with specific functions in the agri-food chain and with the level of technological maturity observed in the current literature (pilot, scaling, broad adoption). This multidimensional approach ensures a comprehensive understanding of the digital transformation process. The CTSAF model describes the convergent integration of emerging digital technologies in agri-food value chains as a systemic process, in which each stage—production, processing, distribution, consumption, and reuse—is supported by technological solutions adapted to its specific needs. Thus, IoT sensors and networks can improve the production stage by monitoring resources and environmental conditions, providing essential data for precision agriculture; blockchain and smart contracts can strengthen the processing and distribution phases through traceability, automatic certification and elimination of intermediaries; while, at the consumption stage, digital traceability and innovative labelling tools increase in transparency and consumer trust, contributing to more informed and responsible purchasing decisions.

In this way, the CTSAF is not just a descriptive taxonomy, but a rigorous analytical framework that integrates the results of the literature with the practical needs of governance and digital transformation. The model provides both a basis for academic comparisons between industries and contexts, and a guiding tool for policymakers interested in accelerating the sustainable digitisation of agri-food chains. The logic scheme of the CTSAF model is shown in Figure 3.

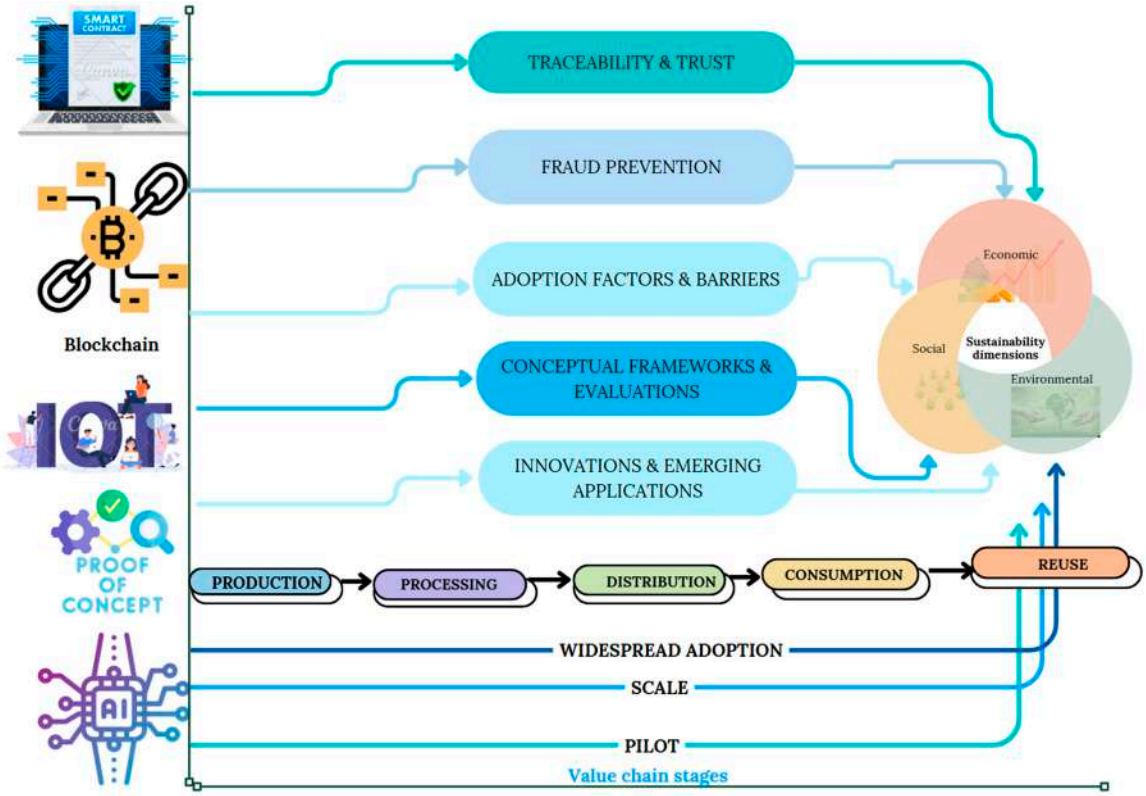


Figure 3. Graphical representation of the CTSAF model (Converging Technologies for Sustainable Agri-Food Chains).

Transforming agri-food chains through the convergent integration of emerging digital technologies is a strategic direction for achieving economic, environmental and social sustainability goals. These technologies, such as blockchain, the Internet of Things (IoT), AI, Smart Contracts, and zero-knowledge proof (ZKP) mechanisms, provide innovative tools to rebuild trust relationships, optimise production and distribution flows, and ensure transparency in agri-food ecosystems. Their transformative potential inspires a new perspective on sustainability in the agri-food industry.

Going beyond a mere descriptive approach, the CTSAF model plays a pivotal role in providing a systemic understanding of how the convergence of digital technologies can bolster the transition to sustainable agri-food chains. This model, articulated in five critical dimensions—traceability, fraud prevention, adoption factors, emerging innovations, and applications—investigates not only direct benefits such as traceability, fraud prevention, and emerging innovations, but also delves into structural challenges, including adoption factors, technological barriers, and a lack of mature conceptual frameworks. By doing so, it not only provides a robust basis for benchmarking but also instils confidence in its ability to guide decision-makers toward sustainable policies and practices.

4.1. Traceability and Trust

The integration of blockchain into agri-food chains creates immutable distributed ledgers that record the provenance of products, production conditions, and associated transactions. This mechanism plays a crucial role in strengthening trust between actors by reducing asymmetric information and guaranteeing the authenticity of data. Traceability thus becomes a fundamental pillar of social sustainability, as it increases food safety and economic sustainability by facilitating access to regulated and certified markets. The CTSAF model begins with the premise that traceability is not merely a technical function of the distributed ledger, but a socio-technical outcome of the convergence of blockchain, IoT, and AI. We thus align with studies showing that layered architectures (physical layer–IoT–blockchain) and smart contracts produce immutable records of provenance, environmental conditions, and transactions, reduce information asymmetry, and an increase in trust between actors [7,38,39,41]. The integration of digital labelling and sensors (RFID/QR/NFC) with distributed ledgers strengthens end-to-end traceability and credibility of information, including in the eyes of consumers, which the literature links to a greater willingness to pay a premium price for "green" and certified products [3,31,81].

4.2. Fraud Prevention

Fraud prevention is closely linked to traceability. By combining blockchain with IoT, information on the status and movement of products is transmitted in real-time and stored securely. Zero-knowledge proofs add an extra layer of security, allowing compliance to be verified without full disclosure of sensitive data. This dimension contributes to consumer protection and to strengthening the credibility of agri-food markets. In the logic of CTSAF, fraud prevention stems from the combination of the immutable ledger with real-time measurement and advanced analytics. We agree with analyses that highlight the role of decentralisation and auditability in authenticity and transparency, as well as evidence that secure IoT $\rightarrow$ blockchain flows reduce opportunities for manipulation [14,78]. Recently, the literature suggests that integrating AI with instrumental methods and blockchain enables the early detection of anomalies and their permanent recording, which is beneficial for assigning responsibility [40].

4.3. Adoption Factors and Barriers

Although emerging technologies offer obvious benefits, the literature reveals multiple obstacles to their adoption, including high deployment costs, a lack of digital infrastructure in rural areas, a low level of technological literacy, and the reluctance of some stakeholders to share data. At the same time, enabling factors include public digitalisation policies, pressure from retail chains for traceability, and consumer demand for sustainable and certified products. Therefore, analysing adoption factors is crucial for understanding the dynamics of the digital transition. The CTSAF places adoption decisions within an expanded TOE (Technology–Organisation–Environment–management) framework, aligning with evidence-based models that distinguish the initiate–adoption–implementation stages and identify critical determinants such as relative advantage, compatibility, cost, organisational readiness, inter-firm trust, and institutional pressures. The model also treats as mandatory contextual variables the regulatory uncertainties, insufficient standardisation, infrastructure barriers, and skills shortages that often keep projects at the pilot level.

4.4. Conceptual Framework and Evaluations

The CTSAF model adds a critical dimension through which not only technological functionalities are analysed, but also how they are reflected in literature and practice. This assessment involves mapping the maturity stage (pilot, scaling, broad adoption) and identifying existing conceptual frameworks and gaps in regulation. Such an integrated approach enables a deeper understanding of the impact of technological convergence in relation to the Sustainable Development Goals and the circular economy. This perspective aligns with recent literature, which confirms that integrating blockchain and associated Industry 4.0 technologies remains a gradual and often fragmented process. Studies show that most initiatives are still at the pilot project stage or in the early stages of sectoral scaling, with rare cases of widespread adoption, where standardisation and regulation facilitate systemic integration [55,100].

4.5. Emerging Innovations and Applications

Digital technologies are evolving rapidly, and recent literature has seen the emergence of innovative applications, such as the use of smart contracts for the automatic certification of organic products, AI algorithms for demand forecasting and waste prevention, or the integration of IoT in the monitoring of refrigerated transport conditions. These applications not only demonstrate the potential of technological convergence to create entirely new, sustainable, and resilient business models but also pave the way for a more optimistic future for agri-food chains. Recent literature confirms that innovations based on the convergence of digital technologies are radically transforming the way agri-food chains are organised and governed. Blockchain, integrated with smart contracts, is applied for the automatic certification of organic products, facilitating rapid compliance verification and reducing administrative costs [5]. At the same time, AI and Big Data play a significant role in supporting demand forecasting and food waste prevention by generating advanced predictive models, while IoT monitors transportation and storage conditions to ensure food freshness and safety [58,102].

The process of technological integration follows a gradual maturation trajectory. In the first stage, the pilot projects function as innovation laboratories, where solutions are tested and conceptually validated. Subsequently, through the scaling phase, the technologies are extended to the sectoral level and empirically validated through concrete applications, confirming their relevance for specific products or industries. In the final stage of widespread adoption, digital solutions become systemic tools, integrated into critical infrastructures, official regulations, and organisational strategies, marking the transition from experiment to a structural transformation of the agri-food sector. The impact of technological convergence is measured in relation to the three fundamental dimensions of sustainability. From an economic point of view, digital integration contributes to increasing operational efficiency, optimising logistics flows, and reducing transactional costs. From an ecological perspective, technologies support the responsible management of natural resources, the reduction of food waste, and the reduction of carbon emissions, aligning with the principles of the circular economy. On a social level, the digitisation of agri-food chains enhances product traceability, increases transparency and consumer trust, promotes equity among stakeholders, and contributes to strengthening food security.

5. Conclusions

The results show that the convergent integration of emerging digital technologies–blockchain, IoT, AI and smart contracts–can represent a strategic direction for strengthening the resilience, transparency and sustainability of agri-food chains.

The critical analysis carried out for RQ1, RQ2 and RQ3 shows that the CTSAF model (Converging Technologies for Sustainable Agri-Food Chains) provides an integrated and systemic framework through which the convergence of emerging digital technologies can support the sustainable transformation of agri-food chains. The critical synthesis of the results, structured around the three research questions, highlights some important conclusions. First, blockchain clearly improves transparency and accountability, which supports consumer trust and more responsible consumption. However, the literature rarely assesses whether these benefits actually translate into circular practices, resource efficiency or measurable waste reduction. Second, studies connecting blockchain with IoT, AI, and Big Data point to promising directions for optimising logistics and monitoring environmental performance. However, the evidence remains conceptual mainly, with very few empirical studies using standardised metrics to quantify economic and ecological gains. Third, although barriers and success factors to adoption are increasingly discussed, most analyses are limited to developed economies. As a result, the challenges and opportunities specific to emerging economies remain a significant gap. In relation to RQ1, regarding the relationship between blockchain and the circular economy, the model confirms that traceability, trust, and emerging innovations (e.g., tokenisation, smart contracts) are central tools for reducing waste, empowering consumers, and strengthening circular models. Thus, CTSAF integrates ecological and social sustainability into food consumption through transparent and participatory digital mechanisms. In relation to RQ2, regarding the integration of blockchain for economic and environmental sustainability, the model shows that blockchain–IoT–AI interoperability optimises logistics flows, reduces losses, and decreases the carbon footprint. By linking these benefits with the dimensions of traceability, trust, and anti-fraud, the CTSAF demonstrates that economic and environmental sustainability can be achieved through a converged approach, where technologies interact along the entire value chain. In relation to RQ3, on barriers and success factors in blockchain adoption, the model integrates the "adoption factors and barriers" dimension, showing that success depends on contextual conditions such as digital infrastructure, organisational readiness, government support, and multi-stakeholder collaboration. The CTSAF confirms that only a systemic, multisectoral and scaled approach can turn pilot projects into mature and widely adopted digital solutions.

Therefore, the unitary answer to the three questions is that the CTSAF model provides a coherent and empirically validated vision on how the convergence of digital technologies (blockchain, IoT, AI, smart contracts, ZKP) can transform agri-food chains into an economically, environmentally, and socially sustainable system. The model is not limited to describing benefits, but also integrates implementation challenges, success factors, and technological maturation trajectories, thus providing an operational framework for decision-makers, organisations, and communities interested in transitioning to resilient, transparent, and circular agri-food chains. The barriers identified in the literature should not be interpreted as definitive obstacles, but as structural challenges that can be transformed into opportunities through a systemic approach. This perspective justifies the need for a conceptual framework such as CTSAF, which integrates technological, economic, organisational, social, and regulatory dimensions, providing a holistic tool for accelerating the sustainable digitalisation of agri-food chains.

5.1. Theoretical Implications

Theoretically, the study makes an important contribution by formulating an integrated conceptual framework that highlights how the convergence of digital technologies–including blockchain, IoT, AI, smart contracts, and ZKP mechanisms–can simultaneously support the economic, ecological, and social dimensions of sustainability. In this regard, the article goes beyond the limited approaches to traceability and safety, proposing an interdisciplinary vision that correlates digitalisation with the circular economy, sustainable governance and the structural transformation of agri-food chains. At the same time, by identifying existing gaps and integrating adoption factors into the CTSAF conceptual framework, the study contributes to the development of new analytical perspectives on technological maturity and the transition to Industry 5.0.

5.2. Practical Implications

On a practical level, the results are addressed to both decision-makers and organisations and communities involved in agri-food chains. The proposed model can guide the development of public policies on digitalisation and standardisation, while providing a strategic tool for companies that want to adopt sustainable digital solutions gradually. Farmers and small businesses can benefit from an increase in opportunities to access premium markets, based on digital certification and reduced information asymmetries, while consumers gain through transparency, trust, and social responsibility. At the same time, the analysis draws attention to practical barriers–including high costs, a lack of digital skills, and reduced interoperability–highlighting the need for support programmes, multi-stakeholder partnerships, and dedicated educational initiatives.

5.3. Future Research Directions

The results obtained in this paper highlight both the transformative potential of technological convergence in agri-food supply chains and the persistent barriers that hinder its widespread adoption. Starting from the CTSAF (Converging Technologies for Sustainable Agri-Food Chains) conceptual model, several relevant directions can be outlined for future research, namely: (1) Validation and extension of the CTSAF model (Converging Technologies for Sustainable Agri-Food Chains) for meat and horticulture. Comparative analyses between developed and emerging economies can provide valuable insights into technological maturity, adoption factors, and context-specific barriers. In addition, the development of standardised performance indicators would allow for a more coherent assessment of the sustainability impact of digital convergence. (2) Integration of emerging technologies (it is necessary to deepen research on the integration of the blockchain with advanced mechanisms such as zero-knowledge proofs (ZKP), multi-chain architectures, and optimised consensus algorithms (e.g., PBFT, SPBFT), in order to meet the challenges of scalability, privacy, and efficiency. At the same time, studies on the interoperability between blockchain, IoT, AI, Big Data, RFID, and digital twins are essential for understanding the synergistic effects on the traceability and resilience of chains. A promising field is also the role of Web 3.0 and Industry 5.0 technologies (e.g., metaverse, collaborative robots, nano sensors) in shaping fully digitised agri-food ecosystems). (3) Socio-economic and environmental impacts (future research should investigate the socio-economic implications of blockchain adoption, in particular its role in supporting smallholder farmers, reducing transactional costs, and facilitating access to international markets. In parallel, assessing the contribution of digital systems to reducing food waste and carbon footprint remains crucial. Studies on consumer behaviour can clarify their willingness to pay a premium price for digitally certified and sustainable products). (4) Factors influencing adoption and public policies (longitudinal research is needed on critical success factors and persistent barriers (lack of infrastructure, high costs, resistance to change). Particular attention should be paid to the role of public policies, regulatory clarity, and public-private partnerships in facilitating accessible and inclusive digital solutions. Exploring incentive mechanisms and governance models can accelerate uptake in resource-limited contexts). (5) Methodological advances (A research direction is the development of holistic assessment frameworks that integrate economic, ecological, social, and political dimensions. The application of multicriteria methods and dynamic system modelling can improve the evaluation of implementation scenarios. Additionally, AI-powered predictive analytics and risk detection tools are worth exploring to strengthen the robustness of blockchain-backed supply chains).

By investigating these directions, future research can evolve beyond descriptive analyses towards applicative and strategic solutions, supporting the transition to resilient, transparent, and sustainable agri-food systems.

5.4. Limitation

Like any systematic review study, the present paper also has certain limitations. The predominantly conceptual and synthetic character of the research does not allow for direct empirical validation of the CTSAF model, which requires further testing in practical and comparative contexts. The methodological heterogeneity of the studies analysed partly limits the generalisation of the conclusions, and the lack of a uniform framework for assessing the socio-economic and environmental impact makes it difficult to compare the results. However, it is precisely these limitations that confirm the relevance and necessity of future research, reinforcing the added value of this study as a starting point for further academic and practical developments.

Overall, the study confirms that the transition to sustainable agri-food chains cannot be achieved without an integrated vision of digitalisation and technological convergence. The CTSAF conceptual model suggested that blockchain, IoT, AI, and smart contracts are not just technical tools but true catalysts for transparency, resilience, and a circular economy. At the same time, the recognition of barriers and critical success factors underlines that digital transformation is a gradual process, dependent on collaboration, public policy and managerial innovation. By addressing these challenges and seizing the opportunities highlighted, research and practice can make a decisive contribution to building fairer, more competitive and future-oriented agri-food systems.

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