frontiers | Frontiers in Sustainable Food Systems

TYPE Systematic Review
PUBLISHED 13 February 2024
DOI 10.3389/fsufs.2024.1347116



OPEN ACCESS

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RECEIVED 30 November 2023
ACCEPTED 19 January 2024
PUBLISHED 13 February 2024

CITATION
Ordoñez CC, Gonzales GR and Corrales JC (2024) Blockchain and agricultural sustainability in South America: a systematic review.
*Front. Sustain. Food Syst.* 8:1347116.
doi: 10.3389/fsufs.2024.1347116



# Blockchain and agricultural sustainability in South America: a systematic review

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In its fundamental role for food security in South America, sustainable agriculture faces the challenge of addressing the current and future needs of the region while ensuring profitability, environmental health, and social and economic equity. Currently, as support for sustainable agriculture, a significant transformation is observed in the agricultural landscape due to the development of advanced information systems. Technologies such as Artificial Intelligence, Machine Learning, and Blockchain have emerged as crucial tools to document and support sustainable agricultural processes. Blockchain technology has proven to be highly beneficial for sustainable agriculture, effectively addressing a significant issue in the agricultural supply chain by providing solutions for transparent and traceable processes. This technology solves the problem by establishing a permanent and open record of all transactions and activities in the supply chain, allowing consumers and stakeholders to track the origin and quality of agricultural products, thereby fostering trust and fair trade. For this reason, this article conducted a review of the current state of blockchain technology in sustainable agriculture, aimed at researchers and farmers in South America. The advantages and disadvantages of blockchain technology were identified, focusing on technologies developed and tested during the design and pilot phases. The PRISMA methodology was used in this review, and documents were searched in Scopus and Web of Science databases. Six hundred and fifty-six articles were identified and selected (2018–2023 period), but only 104 met the eligibility and inclusion criteria. The findings indicate a 30% increase in the adoption of decentralized applications (DAPs) powered by blockchain in the agribusiness sector compared to the previous year. After a thorough analysis, it has been determined that smart contracts, non-fungible tokens for digital assets, and blockchain oracles will provide promising solutions for sustainable agricultural technology in the future.

KEYWORDS

**blockchain, sustainable agriculture, traceability, smart contracts, agribusiness, review**

## 1 Introduction

As a fundamental pillar of food security in South America, sustainable agriculture faces the challenge of meeting the current and future needs of the region while ensuring profitability, environmental health, and social and economic equity (Mba et al., 2020). In this context, sustainable agriculture emerges as an essential pillar, contributing to the four critical aspects of food security: availability, access, utilization, and stability; addressing the environmental, social, and economic dimensions of sustainability outlined by the United Nations Food and Agriculture Organization (FAO) (Resources, Forest, and Assessment Working, 1962).

Currently, a significant transformation is observed in the agricultural sector and its supply chain, encompassing all stages from planting to the end consumer. This process includes activities such as cultivation, harvesting, processing, storage, transportation, and sale, ensuring the efficient delivery of fresh food and agricultural products through the development of advanced information systems that support sustainable agriculture. Technologies like Artificial Intelligence (AI), Machine Learning (ML), and Blockchain have emerged as crucial tools to document and assist agricultural processes (Ordonez et al., 2023). In particular, Blockchain, introduced in 2009 alongside the creation of Bitcoin by Satoshi Nakamoto, is a decentralized network where data is stored and shared among nodes, eliminating central authority (Treiblmaier, 2019). Nodes mutually validate transactions, creating a distributed ledger. Considered a technological innovation, it stands out for its autonomy, anonymity, and data immutability. Interconnected Blockchain forms a distributed database, allowing the storage, linking, and retrieval of transaction information (Zhu and Kouhizadeh, 2019). This technology is used in situations requiring privacy, identity control, and permissions, providing immutability, transparency, and instant security by eliminating intermediaries and ensuring the integrity of information, demonstrating a significant impact on traceability and other aspects of the agricultural supply chain (Li et al., 2021; Song and Li, 2021).

In this context, the essential role of this technology is emphasized in fostering trust and collaboration among various actors in the agricultural supply chain, whether partners or competitors. Blockchain provides end-to-end visibility when working with farm products, recording every relevant event from production to delivery to the end consumer (Astill et al., 2019). This approach ensures traceability and safeguards protection, equity, and confidentiality at each stage of the process, determining and contributing to fulfilling the pillars of sustainable agriculture outlined by the FAO (Reyes et al., 2020).

Blockchain applications go beyond traceability, including transaction certification, smart agriculture, and order logistics management in agribusiness (Westerkamp et al., 2020; Sharma et al., 2022). Although various investigations have been carried out on the subject, this review aims to identify the advantages and disadvantages of the current use of Blockchain to support sustainable agriculture and agribusiness, with an emphasis on its application in South America. It analyzes the advantages and disadvantages of implementation in sustainable agriculture and highlights the usage and development of this technology in South America and its relationship with the sustainability pillars (availability, access, utilization, and stability) defined by the FAO (Reyes et al., 2020).

The PRISMA methodology (Moher et al., 2009) was applied, identifying 656 documents and selecting 17 supporting the relevance of Blockchain in agricultural sustainability. Two research questions were addressed, revealing that the technology is used in four South American countries in various contexts. This includes the development of decentralized applications for food traceability (DAPs), the authentication of originality using Non-Fungible Tokens (NFTs), and the validation of intermediaries through smart contracts. The findings indicate a significant growth in the adoption of this technology. This work is organized into sections detailing the methodology, analyzing the literature, examining the application of Blockchain in sustainable agriculture (with a regional focus on South America), presenting conclusions, and finally outlining future research areas.

## 2 Process methodologic

The purpose of this review aims to identify the advantages and disadvantages of the current use of Blockchain to support sustainable agriculture and agribusiness, with an emphasis on its application in South America (Singh et al., 2022).

Based on this objective, the following research questions (RQs) are posed, guiding the development of the review:

- **RQ1.** What are the advantages and disadvantages of the use and adoption of blockchain in sustainable agriculture?
- **RQ2.** Which South American countries are adopting blockchain technology in their agricultural processes?

To address and answer these research questions and achieve the objective, the methodological procedure based on the phases of identification, selection, eligibility, and inclusion of the PRISMA (systematic literature review) is utilized, as depicted in Figure 1 (Moher et al., 2009).

In the development of phase number 1 of the methodology, the literature search string is defined. This is applied in the most recognized digital libraries that contain the largest number of scientific documents related to this research. In this document, Web of Science and Scopus are used. Similarly, this phase involves establishing the research protocol, which includes defining search terms using keywords and various logical operators such as 'OR' and 'AND', as detailed in Table 1. After obtaining a result of 656 documents, these documents are loaded into tools like ScientoPy to process all the documents. To conclude this phase, it is determined that there are 316 duplicate documents. Therefore, for phase two, there are 340 documents that will be evaluated under the selection criteria.

In Phase 2 of the methodology, the literature selection criteria are applied. For this research, studies are considered relevant if they meet the following criteria: (a) the publication must be a paper presented at a conference or published in a peer-reviewed journal, (b) the articles must fall within the period from 2018 to 2023, (c) articles with small samples, deficient methodologies, or unreliable results, (d) articles that provide only an abstract and do not have access to the full text, and (e) articles only in the English language.

For the language criterion, the decision is made to include only articles in English because it is widely accepted as the predominant language in scientific and technological literature worldwide. Most renowned conferences and scientific journals use English as the primary means of communication, facilitating the global dissemination of research. Additionally, the preference for English helps ensure accessibility and understanding by the international scientific community. The use of a common language simplifies communication and knowledge exchange among researchers from different countries and regions (Hamel, 2007). For details on the number of articles discarded for each criterion, reference can be made to Table 2.

In the third phase, with the remaining 175 articles, exclusion criteria were applied, excluding studies that did not specifically address the use of blockchain technology in sustainable agriculture or agribusiness. All titles, abstracts, and keywords were thoroughly

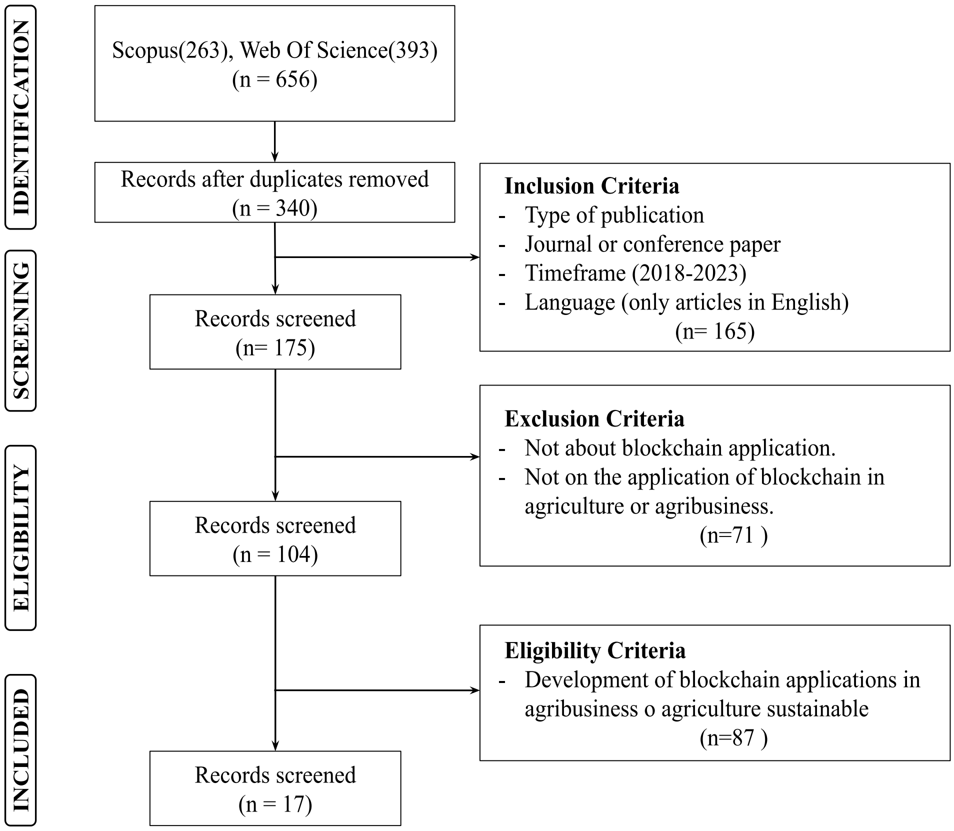


FIGURE 1
PRISMA flow diagram for systematic review.

TABLE 1 Search string.

| Digital Bookstores | Search string design |
|---|---|
| SCOPUS | (TITLE-ABS-KEY (BLOCKCHAIN) AND TITLE-ABS-KEY (TRACEABILITY) OR TITLE-ABS-KEY (AGRICULTURE) OR TITLE-ABS-KEY (AGRIBUSINESS) AND TITLE-ABS-KEY (SUSTAINABILITY)) |
| WOS | ((((TI=(BLOCKCHAIN)) AND TI=(TRACEABILITY)) OR TI=(AGRICULTURE)) OR TI=(AGRIBUSINESS)) AND TI=(SUSTAINABILITY) |

examined at this stage to determine which documents met the criteria. The following statements were used for this purpose:

- The article addresses the subject of blockchain-based applications in smart and sustainable agriculture.
- Articles were sought on the adoption of blockchain technology for smart and sustainable agriculture.
- Specific articles were needed on suggested blockchain architectures and models for sustainable agriculture.
- The article discusses the benefits and barriers of blockchain applicability for smart and sustainable agriculture.
- Among the keywords, "blockchain," "smart agriculture," "enablers," "barriers," "food supply chain," "e-agriculture systems," "traceability," "provenance," "trust," "safety," and "transparency" were identified.

After a comprehensive and meticulous review of the eligible articles, it was determined that a total of 71 articles did not meet the criteria mentioned earlier, resulting in 104 relevant investigations for this review.

In phase four, the inclusion stage of the reviewed articles is carried out, contributing to the development of the overall objective, and addressing the research questions. During this stage, the importance of employing a systematic literature review (SLR) approach to conduct reliable and reproducible literature reviews is highlighted. This involved conducting qualitative analyses and evaluations of relevant articles using thematic analysis to group and synthesize the main themes, thus improving the accuracy and completeness of the data (Carrera-Rivera et al., 2022). Thematic analysis, as described in the work (Braun et al., 2006), encompasses six stages: familiarization with the data, initial code creation, theme identification, review, definition, and naming.

During this stage, it was identified that 87 articles were narrative reviews or purely technical investigations, lacking relevant information on the implementation of blockchain technology in agribusiness and sustainable agriculture. Additionally, they did not focus on developments related to South American countries. Due to this

TABLE 2 Discarded articles due to selection criteria.

| Criteria | Article O conference paper | Period 2018–2023 | Methodology | Articles only abstract | Different English languages | Total articles |
|---|---|---|---|---|---|---|
| NUMBER of articles eliminated | 48 | 69 | 15 | 13 | 20 | 165 |

limitation, the decision was made to disqualify these articles, ultimately including 17 articles for analysis.

Next, in Table 3, the selected articles are presented, classified into two main themes: blockchain and sustainable agriculture, and the role of blockchain in agribusiness. The 17 articles were categorized into these themes, and common patterns among the authors were examined for classification. Consequently, the relevant results and connections that contribute to addressing the research questions are presented.

## 2.1 Results

The relationship between terms and their grouping into various categories is crucial in researching and analyzing a topic. In this context, Figure 2 provides a chronological representation that identifies how words are related and evolve. Understanding and contextualizing vital elements in sustainable agriculture, implementing Blockchain within this context, and effectively focusing and guiding the review are essential. This approach significantly contributes to defining the scope and relevance of the review. Highlighting these terms drives to focus on the most critical and current aspects of the topic, which is essential to ensure that the review is aligned with the latest advancements in sustainable agriculture and the application of blockchain technology.

The ability to track these trends over time yields valuable insights into the trajectory and dynamics of research within this field. The pertinent issues identified through this analysis hold paramount significance today, addressing pivotal concerns within agriculture and the integration of blockchain technology. In yellow, the highlighted topics establish direct connections with the innovation and design of systems incorporating Blockchain and its facilitation of the supply chain and agribusiness. Furthermore, these areas align seamlessly with contemporary applications of blockchain technology, emphasizing innovation and system design alongside its pivotal role in supporting the supply chain and agribusiness.

In the sphere of sustainable agriculture, substantial strides are being taken through the integration of blockchain technology. In this context, pivotal concepts such as economic growth, agroecology, yield, quality, intensification, wheat, biochar, financial sustainability, social sustainability, and performance have surfaced as this state-of-the-art technology's primary focal points and integral applications.

This term analysis aims to examine the correlation between these terms and the countries incorporating technology into their sustainable agricultural practices since the identification of the technology started with the first publications on the subject, where relevance is observed to have emerged since the year 2009. Globally, it can be observed that the United States leads developments in blockchain technology in sustainable agriculture, followed by India, Italy, the United Kingdom, China, Spain, France, Brazil, Canada, and Australia. This ranking is derived from the total number of articles on the implementation of blockchain in agricultural processes, categorized by those published before and after 2021, as identified in different geometric figures, as shown in Figure 3. Notably, Brazil (gray circle) has emerged as a leading country in South America, showing significant adoption of blockchain technology in its sustainable agricultural processes. For a deeper examination of the contributions of this country, the research includes a dedicated section where the contributions of this technology in individual countries are determined and analyzed.

Based on this analysis, the description of the selected articles, categorized into two groups, contributing to answering the research questions, proceeds as outlined below.

## 2.2 Blockchain sustainability

Blockchain technology, as a distributed ledger system, has emerged as a critical enabler for enhancing sustainable agriculture, agricultural resource management, innovation in agriculture, urban agriculture, and agribusiness. The following paragraphs describe the most relevant results obtained through this technology.

Saberi et al. (2019) investigate the adoption barriers of Blockchain technology in the supply chain, affecting partners, employees, and stakeholders. They highlight technological barriers stemming from the technology's immaturity, emphasizing the need for further research in scalability. They also propose areas of study to address post-adoption issues and recommend implementing standards and regulations to ensure Blockchain's interoperability and security in the supply chain.

The article Dos Santos et al. (2021) proposes using smart contracts and non-fungible tokens (NFTs) as an efficient and fraud-resistant tool to demonstrate the sustainability of specific crops. This technology enables farmers to be certified by any authority, extending their certificates as NFTs throughout the supply chain to the consumer. Furthermore, it emphasizes the presence of economic incentives for participants, encouraging adoption and promoting sustainability while combating "greenwashing."

Implementing blockchain technology in supply chain management aims to promote sustainability in various regions, including countries like China and South Africa. Notably, blockchain adoption in supply chain management is occurring globally, encompassing developed and developing countries. In this context, eight key themes motivating the adoption of this technology in the agri-food supply chain have been identified Kshetri (2021). These themes range from the need to ensure traceability and transparency of food to facilitating financing and market access, thus promoting sustainability and social responsibility Yogarajan et al. (2023). However, critical research gaps are highlighted, such as the lack of studies in diverse cultural environments, limited research on logistical

TABLE 3 Summary of the identified studies and their correlation with the RQs.

| Item | Cited by | Title | Author | Group | RQs |
|---|---|---|---|---|---|
| 1 | 1,539 | Blockchain technology and its relationships to sustainable supply chain management | Saberi et al. (2019) | Blockchain sustainability | RQ1 |
| 2 | 26 | Third party certification of agri-food supply chain using smart contracts and blockchain tokens | Dos Santos et al. (2021) | Blockchain sustainability | RQ1 |
| 3 | 98 | Exploring the hype of blockchain adoption in agri-food supply chain: a systematic literature review | Yogarajan et al. (2023) | Blockchain in agribusiness | RQ1, RQ2 |
| 4 | 91 | Blockchain and sustainable supply chain management in developing countries | Kshetri (2021) | Blockchain sustainability | RQ1, RQ2 |
| 5 | 75 | Blockchain as a sustainability-oriented innovation? Opportunities for and resistance to Blockchain technology as a driver of sustainability in global food supply chains | Friedman and Ormiston (2022) | Blockchain sustainability | RQ1, RQ2 |
| 6 | 53 | Toward an agriculture solution for product supply chain using Blockchain: case study Agro-chain with BigchainDB | Orjuela et al. (2021) | Blockchain in agribusiness | RQ1 |
| 7 | 33 | Analysis of Blockchain's enablers for improving sustainable supply chain transparency in Africa cocoa industry | Bai et al. (2022) | Blockchain in agribusiness | RQ2 |
| 8 | 10 | A critical analysis of the integration of Blockchain and artificial intelligence for supply chain | Charles et al. (2023) | Blockchain sustainability | RQ1 |
| 9 | 14 | An evidence of distributed trust in blockchain-based sustainable food supply chain | Joo and Han (2021) | Blockchain sustainability | RQ1 |
| 10 | 11 | The potential of blockchain technology in the transition toward sustainable food systems | Wünsche and Fernqvist (2022) | Blockchain sustainability | RQ1 |
| 11 | 9 | Blockchain technology in wine chain for collecting and addressing sustainable performance: an exploratory study | Luzzani et al. (2021) | Blockchain in agribusiness | RQ2 |
| 12 | 4 | Design of a blockchain-based decentralized architecture for sustainable agriculture: research-in-progress | Akella et al. (2021) | Blockchain in agribusiness | RQ1 |
| 13 | 6 | Smart contract for coffee transport and storage with data validation | Valencia-Payan et al. (2022) | Blockchain sustainability | RQ2 |
| 14 | 52 | Using system dynamics to analyze the societal impacts of blockchain technology in milk supply chainsrefer | Mangla et al. (2021) | Blockchain in agribusiness | RQ1 |
| 15 | 4 | Smart contract and Web DApp for traceability in the olive oil production chain | Fernandes et al. (2022) | Blockchain sustainability | RQ1 |
| 16 | 14 | Blockchain is not a silver bullet for agro-food supply chain sustainability: Insights from a coffee case study | Bager et al. (2022) | Blockchain in agribusiness | RQ1, RQ2 |
| 17 | 3 | Blockchain trust impact in agribusiness supply chain: a survey, challenges, and directions | Nasir et al. (2022) | Blockchain in agribusiness | RQ1 |

and operational effects, absence of studies on quality management in blockchain adoption, lack of consideration for socio-environmental costs, and limited research on the impact in developing countries.

In Friedman and Ormiston (2022), a methodology is proposed based on interviews with experts in food supply chains, providing a comprehensive view of the use of Blockchain as both a practical tool and a philosophy to address sustainable challenges. The study identifies various forms of resistance, including functional and psychological barriers and obstacles to implementing the technology. It contributes significantly to the literature on sustainability-focused innovation and innovation resistance theory by shedding light on blockchain technology's role and perceived limitations in food supply chains.

On the other hand Bai et al. (2022), based on the theoretical framework of Technology-Organization-Environment (TOE), present a hierarchical enabling framework to enhance the transparency of Sustainable Supply Chain (SSCT) through blockchain technology in the cocoa industry. Using the Best-Worst Method (BWM), the weights of the main facilitators and sub-facilitators are evaluated in a real case of the cocoa supply chain in an emerging African economy.

The results highlight that "Technical Characteristics" are the leading facilitator, and the most significant sub-facilitators include "blockchain smart contract," "blockchain security," and "product component tracking. This approach provides decision-makers and supply chain managers with a framework and method to develop effective strategies for blockchain implementation, thereby improving SSCT.

In Valencia-Payan et al. (2022), a smart contract is designed to carry out traceability and monitoring of the stages of transportation and storage, as well as the condition of coffee beans. The smart

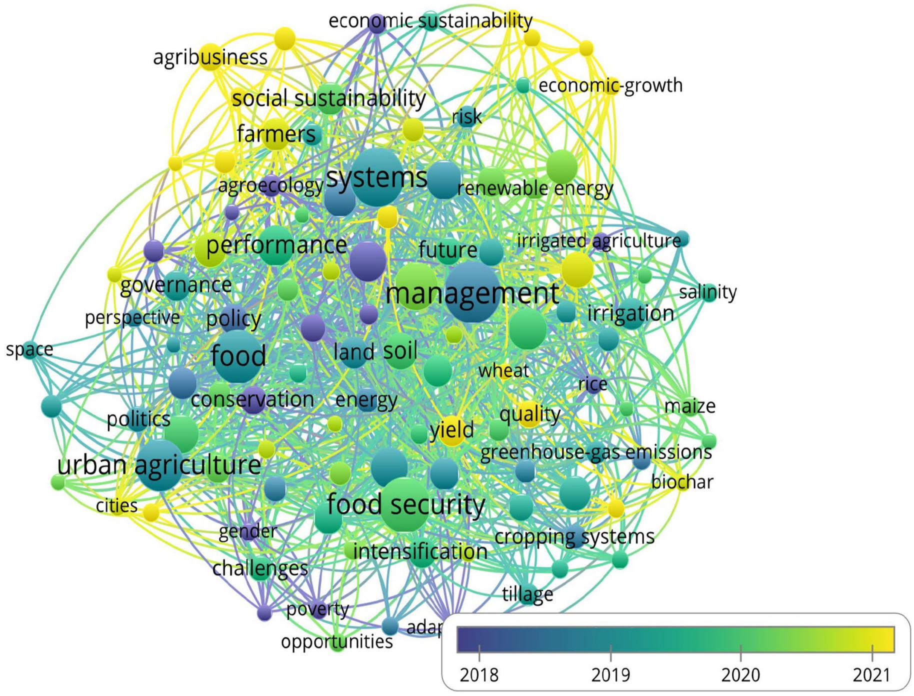


FIGURE 2
Topics related to the adoption of Blockchain in sustainable agriculture.

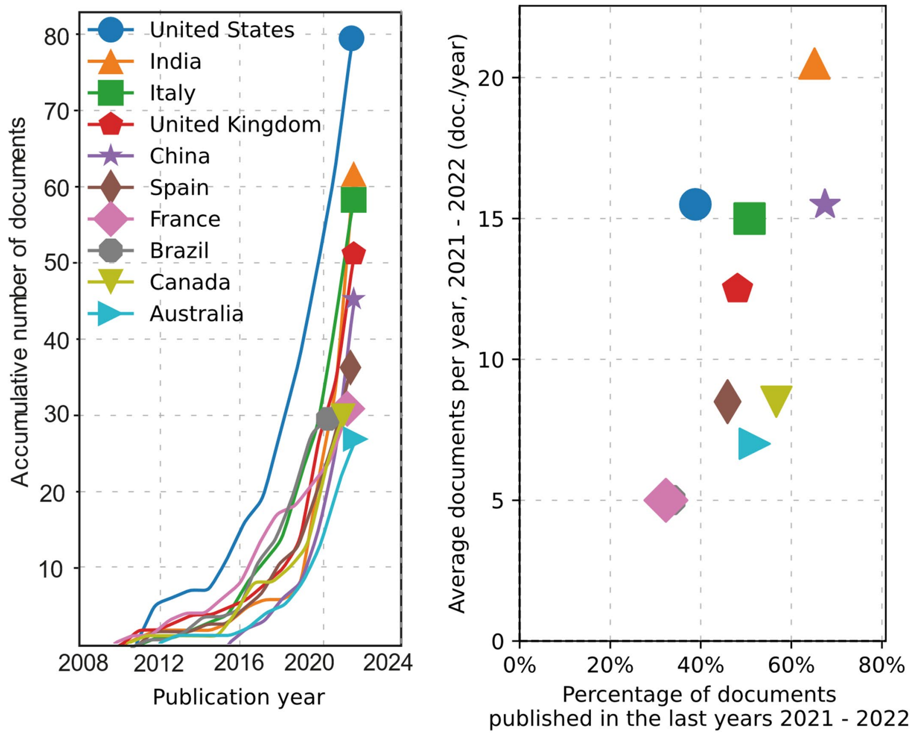


FIGURE 3
Work related to Blockchain and agriculture worldwide, before and after 2021.

contract collects data from sensors placed in coffee bags. It validates the information to ensure that the coffee beans are transported and stored under appropriate conditions, verifying humidity and temperature. It contributes to the farmer making informed decisions regarding pre-sale management and achieving better profits by considering coffee certification schemes.

The study Joo and Han (2021), explores the preference for private or permissioned blockchains, such as Hyperledger Fabric, compared to public blockchains for supply chain management. Food safety emerges as a primary concern, and the adoption of permissioned blockchains since 2018 has enhanced transparency, traceability, and security in the supply chain. Additionally, an analysis of the determinants of distributed trust in the blockchain-based supply chain is conducted, emphasizing the critical importance of transparency, traceability, and security to foster trust and user satisfaction in a sustainable supply chain. In this context Akella et al. (2021), an architecture designed for real-time operations using Blockchain, an area that has been scarcely studied so far, is proposed. Implementing this architecture has identified gaps, and work is currently underway to integrate smart contracts to achieve efficient and sustainable agriculture. The anticipated results will benefit agricultural value chains, intermediaries, farmers, and food suppliers in Australia.

Based on Fernandes et al. (2022), the authors design a software solution by implementing blockchain technology and smart contracts to ensure the traceability of olive oil. It was identified that, when making their purchases, consumers focus not only on food brands but also on characteristics such as nutritional value and sustainability. These aspects are directly linked to all stages of the value chain. The smart contract design ensures that this information is accessible and reliable for consumers, strengthening their trust. The proposal focuses explicitly on traceability in the production chain, addressing indicators of quality, social sustainability, and environmental sustainability.

## 2.3 Blockchain in agribusiness

Likewise Charles et al. (2023), explored the integration of artificial intelligence (AI) with blockchain technology as a promising strategy to address challenges in supply chain management. Combining both is a strategic solution, generating benefits such as more solid results. The fundamental reason for this research lies in the ability of these technologies to overcome limitations and improve various aspects of supply chains. By analyzing large volumes of data, AI powers decision-making and predictive analysis in chain management, offering an advanced and automated approach to extracting valuable information from historical data, such as predicting future demands and forecasting sales, thus contributing to agribusiness.

This research Wünsche and Fernqvist (2022) establishes a study to compare supply chains with Blockchain, proposing investigations into blockchain service design, user experiences, and practical issues in the documentation and certification of current systems. It suggests the inclusion of qualitative assessments of companies throughout the chain, including farmers and small agri-food businesses. It advocates for quantitative studies with the food industry to deepen understanding and improve standards for data exchange and transparency, considering the role of policies. Additionally, it proposes comparing the environmental sustainability of conventional food systems and those facilitated by blockchain, using tools such as life cycle assessment for quantitative reasoning on the value blockchain can contribute to more sustainable food systems.

In Luzzani et al. (2021), exploratory research was designed to investigate the potential benefits and challenges of implementing blockchain technology in the wine industry. Divided into three phases, it addressed specific questions. A systematic literature review was conducted in the first phase on using Blockchain in supply chain and sustainability. The second phase involved surveys of wineries, assessing their knowledge and willingness to adopt Blockchain. The third phase included qualitative interviews with a winery that had already implemented the technology. The study identified benefits such as improved transparency and traceability, data collection on the sustainable performance of wine producers, and enhanced communication among supply chain actors. It also highlighted success stories like the AgriDigital platform in Australia and TE-FOOD in Europe. The need for increased blockchain adoption and data privacy and security considerations for agribusiness development were emphasized. Based on Mangla et al. (2021), the crucial importance of transparency, traceability, and security provided by blockchain technology is established as effective measures against corruption and fraud in the system. An exploration is conducted into the social impacts resulting from the introduction of blockchain technology in the milk supply chain, considering aspects such as rural development, food fraud, animal health, and food safety. The proposal to map and analyze milk supply chains aims to improve social sustainability, seeking to understand how the adoption of blockchain technology influences society and identify opportunities for agribusiness and specific application areas in these supply chains. Orjuela et al. (2021), propose designing and developing a blockchain technology-based platform to enhance traceability and transparency in the agricultural supply chain. The platform utilizes a blockchain database in BigchainDB to store information about farm products, including their origin, quality, and location. It also employs a business model based on smart contracts to automate negotiation and payment processes within the supply chain. Furthermore, it suggests using technologies such as RFID and GPS to improve the accuracy of product location information.

In Bager et al. (2022), the potential of blockchain technology to enhance sustainability in coffee supply chains was assessed, focusing on traceability and transparency. While the pilot implementation highlighted benefits, it also indicated that blockchain technology is not a universal solution to the sustainability challenges of the coffee industry. Despite its reputation as the ultimate system for transparency and sustainability, the study suggests that the true strength of blockchain technology in agri-food chains might lie in the digitization of the supply chain to increase efficiency and reduce costs, disputes, and fraud. The analysis revealed that blockchain implementation can be costly and offer few benefits in cases like non-segregated chains with numerous small-scale farmers. Although specialized chains might be ideal candidates, the additional value of Blockchain could be limited. Furthermore, the importance of digitization to enhance efficiency and transparency was emphasized, indicating that centralized digital solutions could be equally effective. The study underscores the need to understand and minimize real-world barriers before fully leveraging the benefits of digitization and decentralization.

Finally, Nasir et al. (2022), a state-of-the-art review is conducted with the primary objective of presenting the evolution of Blockchain technology, focusing on enhancing trust in the management of agribusiness supply chains and addressing trust inefficiency issues. The research centers on the agribusiness supply chain networks, analyzing issues related to building trust networks based on Blockchain among participants in the data exchange throughout the information flow of the supply chain. Additionally, the paper addresses the research challenges during the design and explores potential solution directions for agribusiness.

## 3 Discussion RQ1, RQ2

In the upcoming sections, we will delve into the findings that stem from the research questions, which played a pivotal role in shaping this systematic review.

> RQ1: ¿What are the advantages and disadvantages of blockchain use and appropriation in sustainable agriculture?

Figure 4 graphically represents the advantages and disadvantages of blockchain technology in sustainable agriculture. Based on this review, we are prepared to address the research question.

Implementing blockchain technology in sustainable agriculture has brought various benefits and disadvantages. Regarding the advantages, transparency stands out by allowing the secure recording of data to trace the origin of agricultural products, which is essential to ensure their sustainability and traceability in the food supply chain (Wünsche and Fernqvist, 2022). The outstanding efficiency in data management through blockchain technology becomes a key focal point in sustainable agriculture. This innovation enables a secure and immutable data record and is prioritized as a fundamental element to drive transparency and traceability throughout the agricultural supply chain. The tool's capability to securely trace the origin of products ensures authenticity and directly translates into the related sustainability of such products. In this context, data management efficiency through blockchain becomes the essential tool to identify sustainable agricultural practices and expose any harmful activities to the environment, ensuring sustainability certificates and organic product labels, combating fraud in the industry, and empowering consumers (Song, 2020).

The use of blockchain for traceability is evident in systems designed and implemented in agricultural products such as coffee, oil, wine, and meat. This approach has significantly contributed to the sustainable development of farming processes. Applying blockchain in these sectors promotes sustainable agricultural practices and gives consumers greater confidence in the origin and quality of products (Valencia-Payan et al., 2022).

On the other hand, there are significant drawbacks; farmers face substantial barriers when adopting blockchain technology, primarily due to associated costs. Specialized technological infrastructure, customized development, and personnel training in blockchain incur significant initial expenses. Integrating with existing systems and the need for technical personnel to manage and maintain the technology adds layers of investment. Maintenance and update costs escalate the financial burden over time. In agricultural settings, particularly in rural areas or developing countries, these costs can pose a significant barrier to the widespread adoption of blockchain technology (Kshetri, 2021).

The scalability of the blockchain is another challenge, as processing speed can decrease as more data is added. It can be problematic in environments with high transaction volumes, such as large-scale agriculture (Sundarakani et al., 2021).

The dependence of blockchain connectivity in the developing agroindustry emerges as a critical factor in its implementation. The effectiveness of this technology is intrinsically linked to the availability and quality of internet connectivity. The ability to transmit data efficiently and in real-time, crucial for traceability and transparency in the agricultural supply chain, requires a robust connectivity infrastructure. In rural environments or developing regions where connectivity infrastructure may be limited, dependence on a blockchain can pose substantial challenges (Yogarajan et al., 2023).

Similarly, the lack of alignment between existing regulations and the decentralized nature of blockchain creates uncertainty and complexities for participants in the agricultural industry. Ambiguities in aspects such as ownership and data management can slow down adoption. Furthermore, the rapid evolution of technology may outpace existing regulatory frameworks, leading to gaps in oversight. Despite these concerns, well-designed regulation could provide a robust legal framework, addressing privacy and security, thus promoting trust and widespread adoption (Singh and Vishwakarma, 2022).

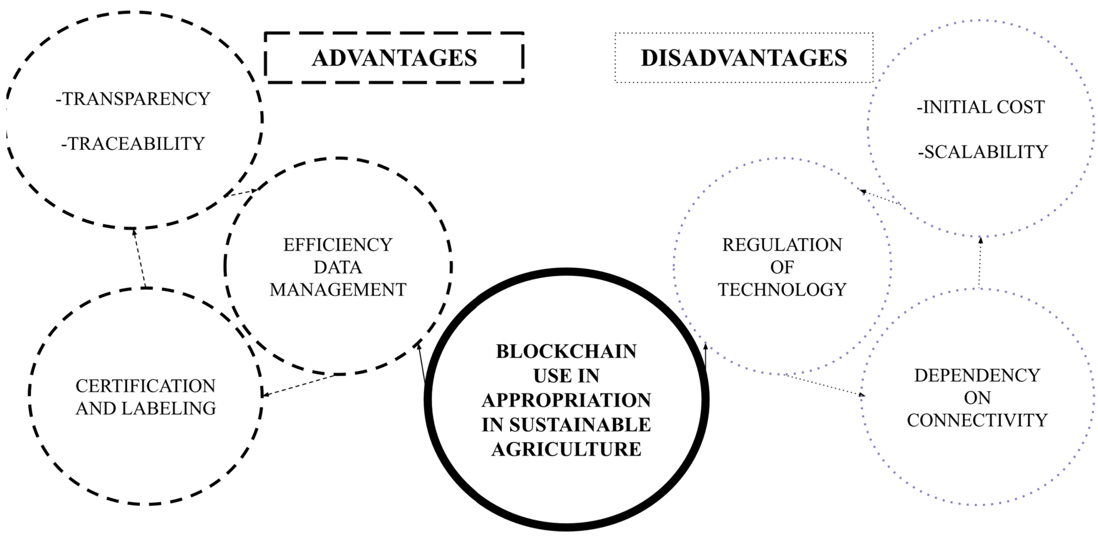


FIGURE 4
Advantages and disadvantages of blockchain technology in sustainable agriculture.

Furthermore, using smart contracts and cybersecurity in agriculture raises some criticism and concerns. Some of them are:

- Technical complexity: Implementing smart contracts and integrating Blockchain into the agricultural supply chain requires advanced technical knowledge, challenging farmers and other stakeholders unfamiliar with these technologies (Quayson et al., 2021).
- Data privacy: The use of Blockchain meant that data was permanently stored and accessible to all participants in the network, raising concerns about the confidentiality of sensitive data such as financial information or farmers' data (Kshetri, 2021).
- Scalability: The ability of blockchain technology to handle large volumes of transactions may be limited, which represents an obstacle to its large-scale implementation in the agricultural supply chain, where numerous transactions are generated daily (Sundarakani et al., 2021).
- Costs: The adoption of smart contracts and Blockchain involves significant costs, such as investment in technological infrastructure and network maintenance, as a barrier to the participation of small farmers or companies with limited resources (Joo and Han, 2021).
- Interoperability: The lack of common standards and protocols in blockchain technology creates difficulties in interoperability between different systems and platforms, limiting the ability of agricultural supply chain actors to collaborate and share data efficiently (Singh and Vishwakarma, 2022).

> RQ2: ¿Which South American countries are adopting blockchain technology in their agricultural processes?

The adoption of blockchain technology in the agribusiness sector in South America is experiencing steady growth, driven by determining factors. Essentially, Blockchain has proven to be a highly effective solution for addressing challenges related to transparency and traceability in the agro-industrial supply chain (Sadiq and Anal, 2023). In response to the increasing demand from consumers who seek precise knowledge about the origin and history of the products they consume, blockchain technology enables detailed tracking from the moment of production until it reaches the consumer's table. This phenomenon is evident in countries such as Colombia and Chile see Figure 5 (Abad-Segura et al., 2021; Orjuela et al., 2021; Bager et al., 2022), where traceability systems and strategies have been recently implemented in agricultural processes. According to the FAO, this initiative is directly linked to the access pillar, which determines the best practices used in agriculture, livestock, forestry, and fishing.

Brazil stands out as one of the prominent leaders in adopting blockchain technology, developing various applications for specific purposes. Its pivotal role in enhancing the supply chain and transparency in South American agribusiness is noteworthy, with food security being a key pillar for the country. The applications designed and linked to Brazil focus on determining the quality and safety of agricultural products (Dos Santos et al., 2021).

On the other hand, Peru is the most recent country to join the adoption of this technology, directing its efforts toward optimizing processes related to the FAO pillar of availability. In this context, they have developed blockchain-based components to identify the production, imports, storage, and tracking of crops, all to ensure the integrity of data and information associated with each (Abad-Segura et al., 2021).

South American countries have delved deeper into blockchain technology within the agribusiness sector, revealing varying degrees of reach and adoption across the region. The following section provides an overview of the advances and studies using blockchain technology in agricultural processes.

- In Brazil, a mobile application was developed to certify the agri-food supply chain through smart contracts and blockchain tokens. It allowed farmers to request inspections for their wine harvests, issuing blockchain tokens that authenticated the quality and authenticity of the harvest. Consumers could verify the authenticity of the certificate by scanning the product. The application used ERC-1155 NFT and ERC-20 tokens to represent harvests and certificates, being implemented on Ethereum through smart contracts in Solidity. Public access to the source code of the smart contracts on the Ethereum network was provided for consumer audit and review (Dos Santos et al., 2021).
- The authors advocate for adopting blockchain technology in coffee supply chains in Colombia to enhance sustainability (Bager et al., 2022). Emphasizes the strength of blockchain in digitizing the supply chain, improving efficiency, and reducing costs, disputes, and fraud in agri-food chains. The importance of understanding and minimizing real-world barriers before fully leveraging the benefits of digitization and decentralization is underscored. In contrast, (Valencia-Payan et al., 2022) propose a smart contract to trace coffee beans' transportation and storage stages, monitoring their condition based on humidity and temperature. The proposal pursues greater traceability and quality control in the supply chain.
- In Chile, a study was conducted to identify emerging trends in blockchain technology research for secure accounting management. Reliable quality indicators were obtained by applying mathematical and statistical techniques to a sample of 1,130 articles from Elsevier's Scopus database. The study demonstrated the usefulness of blockchain technology in areas such as supply chain and logistics, providing solutions for traceability and transparency. It also highlighted new research areas like Blockchain and data privacy, cybersecurity, digital identity, and renewable energy systems. The findings are relevant for academics, researchers, and blockchain developers (Abad-Segura et al., 2021).
- In Peru, a review of the state of the art focused on agriculture and smart contracts to explore how blockchain technology and smart contracts enhanced transparency, traceability, and quality control in the agri-food supply chain. It was emphasized that the combination of Blockchain, the Internet of Things (IoT), and smart contracts enabled a transformed digital agricultural ecosystem where traceability and verification of food quality were achieved reliably and transparently. Additionally, it was highlighted that blockchain-based smart contracts helped address food safety issues by documenting all transactions in a distributed manner and maintaining an immutable record of the same (Charles et al., 2023)


FIGURE 5
Countries that use Blockchain and their relationship with the pillars of sustainability.

After conducting this analysis on the adoption of technologies in sustainable agricultural processes in South America, the economic diversity of the region becomes evident, with countries at different stages of development. This diversity directly impacts the availability of resources and investment in technologies such as blockchain. The technological infrastructure varies between regions, influencing the adoption of blockchain in agriculture based on connectivity and access to emerging technologies. While Brazil stands out as a powerhouse in South America and a pioneer in regional technological development, each country has specific characteristics, such as predominant crop types and agricultural practices, that influence the adoption of technologies like blockchain (Da Silveira et al., 2023). To incorporate this technology in other South American countries, there is a perceived need for government regulations, educational awareness, local initiatives, collaborations, and governmental support as key factors for adoption.

In contrast, in countries like the United States, China, and European countries, the implementation of blockchain technologies occurs gradually, addressing different services. These countries make significant investments to enhance supply chain management and traceability of agricultural products, utilizing blockchain to address authenticity, transparency, and product security (Samadhiya et al., 2023).

## 4 Conclusions and future work

After conducting this comprehensive review, it is concluded that blockchain technology emerges as an essential tool in sustainable agriculture and the traceability of agricultural products. The immutability and transparency of Blockchain ensure the integrity of records throughout the supply chain, not only promoting food safety by enabling swift responses to potential issues but also empowering consumers by providing verifiable information about the origin and quality of the products they purchase. This transparency is crucial for driving the demand for environmentally friendly and ethical products while rewarding farmers who embrace sustainable practices. Blockchain technology is a fundamental pillar for effectively and transparently addressing these challenges in an increasingly sustainability-conscious world concerned with food traceability.

The introduction of blockchain technology in sustainable agriculture has marked a significant advancement, albeit not without challenges. The transparency achieved through secure data recording has been crucial for confidently tracing the origin of agricultural products, enhancing their authenticity in the context of sustainability, and establishing effective traceability in the food supply chain. Identifying sustainable practices and exposing harmful environmental activities has proven to be a valuable tool.

However, drawbacks such as initial costs have acted as barriers to widespread adoption, especially in rural areas or developing nations. The need for training, the scalability challenge, and the reliance on a robust internet connection are critical aspects that require attention. The technical complexity, concerns about data privacy, scalability issues, costs, and interoperability in using smart contracts and cybersecurity in agriculture underscore the importance of addressing these aspects to maximize the benefits of blockchain technology in the agricultural domain. Despite the challenges, successful implementation has the potential to transform agriculture into a more sustainable and efficient model, providing a foundation for future development in this sector.

The adoption of blockchain technology in the agribusiness sector of South America is experiencing steady growth, serving as an effective solution to address transparency and traceability challenges in the supply chain. Brazil leads this revolution, supported by abundant research highlighting its applications and advantages in agribusiness.

Case studies in South America reveal blockchain technology's significant impact and versatility in agricultural supply chains. The Brazilian case highlights the successful implementation of Blockchain, smart contracts, and NFTs to certify wine harvests, enhancing authenticity and transparency for consumers. However, the Colombian study emphasizes the variability in the effectiveness of Blockchain, especially in non-segregated chains with small coffee farmers, underscoring the need for adaptive approaches. The Chilean research demonstrates the evolution of Blockchain into crucial areas such as data privacy and cybersecurity, expanding its utility in logistics and supply chain management. The Peruvian review underscores the transformative potential of Blockchain and smart contracts, ensuring traceability and food safety in a digitized agricultural ecosystem. The analysis of these valuable perspectives on the present and future of Blockchain emphasizes its essential role in the transparency and sustainability of agri-food chains, with the need to adapt according to the specific characteristics of each chain.

As a future endeavor to contribute to this field, efforts should be focused on addressing the identified challenges in this review. An example of this is to include strategies for reducing technology implementation costs in agriculture, especially for small farmers. Additionally, it is crucial to develop tailored training programs for farmers, providing them with the necessary skills and knowledge about the technology. Comprehensive cost–benefit analyses of its implementation and the design and establishment of interoperability standards are required, considering long-term impact assessments. Collaboration on policy recommendations is essential to guide the development of supportive regulatory frameworks that encourage responsible adoption of Blockchain in agriculture. These efforts aim to make blockchain technology more accessible, cost-effective, and impactful in transforming agriculture toward sustainability, requiring collaborative endeavors from researchers, policymakers, and stakeholders to overcome existing barriers and foster widespread adoption.

Furthermore, as future work, the need to review a greater number of articles is highlighted in order to carry out a comparison between South America and the development and implementation of blockchain in pioneering countries such as the United States, China, and European countries. For this, Spanish and Portuguese languages must be considered to obtain a broader scope of literature. This comparison is timely as these countries implement technology in their agriculture sustainably, following different standards. This analysis would not only identify best practices but also foster a more effective adoption of the technology, contributing to defining levels of technological integration in sustainable agriculture. This approach is essential for establishing robust practices and regulatory and educational frameworks, facilitating the successful adoption of the technology in diverse geographical locations.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

CO: Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing. GG: Conceptualization, Investigation, Methodology, Resources, Validation, Visualization, Writing – review & editing. JC: Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Writing – original draft, Writing – review & editing.

## Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This work is within the framework of the research project "Incremento de la Oferta de Prototipos Tecnológicos en Estado Pre-Comercial Derivados de Resultados de I + D Para el Fortalecimiento del Sector Agropecuario en el Departamento del Cauca" (grant no: BPIN 2020000100098), founde by Sistema General de Regalías (SGR) de Colombia.

## Acknowledgments

The authors are grateful to the Telematics Engineering Group (GIT) of the University of Cauca, and the Sistema General de Regalías de Colombia (SGR).

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note



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