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Evaluation of blockchain technology in the three dimensions of sustainability and sustainable development goals: a systematic literature review

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Abstract: It is argued that technologies of the Industry 4.0 can impact on sustainable development. This paper aims to evaluate blockchain technologies in order to understand their impact on the dimensions of sustainability and drive in which marks of the sustainable development goals it has the capacity to contribute to its achievement. A systematic literature review was carried out and it was found that there is a predominance of applications on the economic and environmental dimensions in private sector, while social results are largely linked to public administration challenges. It was found that blockchain can support the achievement of sustainable development goals, with the exception of poverty, quality education, gender equality and partnerships for the goals, which were not found in the literature. Finally, there are some barriers to the implementation of blockchain as a support tool for sustainability such as low dissemination and high cost, energy consumption and processing time.

Keywords: sustainability; environmental; economic; social; blockchain; sustainable development goals; systematic literature review.

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1 Introduction

Industry 4.0 is pointed out as a major transformative force, which is capable of changing the paradigms of traditional business models and promoting the development of autonomous factories and with intelligent decision-making processes (Bai et al., 2020).

Industry 4.0 seeks commercial development and overcoming current challenges such as competition and global competitiveness, market volatility and product life cycle demands. Industry 4.0 technologies such as blockchain, Internet of Things (IoT), Cyber-Physical Systems, Additive Manufacturing, Artificial Intelligence, and Big Data, among others, have potential to positively impact business growth and also the social and environmental areas of sustainability (Bai et al., 2020).

Schulz et al. (2020) underscore the importance of fostering research that integrates sustainability and digitalisation in an interdisciplinary manner. On the one hand, this will fill the gaps in the literature; however, it will also enable looking into how digital technologies can support transformations stemming from sustainability.

Blockchain, Internet of Things and artificial intelligence technologies have great capacity to change routines and management in supply chains. Blockchain, for example, enables real-time monitoring of goods handling and transportation, passenger tracking, identity management, among others. Traditional supply chain management systems are being remodelled due to the advent of blockchain technology, so as to optimise their operations and create customer value (Di Vaio and Varriale, 2020).

According to França et al. (2020), blockchain is a technology used mainly in financial transaction services and smart contracts, but currently its application has been expanded in other sectors, including businesses with sustainable strategies.

Blockchain can positively impact sustainability actions due to its reliability and ability to increase transparency, traceability and promote the inclusion of different players in decision-making (Schinckus, 2020).

It blockchain has potential to make a positive contribution to various elements associated with sustainability, such as education, health, social inclusion, the environment, and the local economy (França et al., 2020).

A sustainable operation is understood as a set of processes and activities that cause controlled and minimised impacts on the social, economic and environmental dimensions, so production complies with the limits established in each aspect of sustainability. Complying with these limits through blockchain technology is a key factor in supporting companies to achieve sustainability (Di Vaio and Varriale, 2020). In addition to the results in the economic dimension, blockchain can support the tracking and validation of environmental and social aspects such as security, health, prevention of fraud and corruption, preservation and monitoring of ecosystems, and inspection and trade in carbon credits (Kouhizadeh et al., 2021).

Dantas et al. (2020) argue that efficient sustainable performance in an institution can be attained by using innovative technologies, such as the elements of Industry 4.0 that have great potential to support the achievement of the Sustainable Development Goals.

According to Di Vaio and Varriale (2020), there is a greater number of studies in the literature that correlate blockchain technology with the environmental and economic dimensions, but there is little mention of the social aspect linked to this technology.

According to Balzarova and Cohen (2020), blockchain can aid in monitoring the execution of human rights, such as inspection of working conditions, inspection of child and slave labour, and measurement of employee exposure to toxic agents.

In addition, according to Bai et al. (2020), few papers integrate the conjunctures of sustainability and Industry 4.0, such as the implementation of blockchain as a supporting factor in sustainable development. According to Nayak and Dhaigude (2019) and Saberi et al. (2019), blockchain technology will be fundamental in tracking problematic situations that can create insecurity in the areas of health, environment and society. Lund et al. (2019) show that blockchain technology has great potential to solve issues related to the Sustainable Development Goals created by the United Nations.

In this context, this work seeks to trace the impact of blockchain technology on the three dimensions of sustainability – economic, environmental, and social – through a systematic literature review.

1.1 Research problem

The research problem consists in answering the question: "How does the use of blockchain positively impact the economic, social and environmental dimensions of sustainability?"

1.2 Objectives

This paper aims to evaluate blockchain technologies in different institutions in order to understand their results and impact on the economic, environmental and social dimensions of sustainability.

Furthermore, the specific objectives are

- pointing the list of keywords in the papers of the systematic review by mapping through the Vosviewer software
- analysing positive impacts of blockchain use in the conduct of sustainable actions

- guiding in which targets of the sustainable development goals the blockchain technology has the capacity to contribute to its achievement.

1.3 Academic and managerial implications

It describes the managerial implications by nature of action and thinking. It's been seen that the implementation of the blockchain in order to generate positive impacts on the dimensions of sustainability may cause consequences in the thinking of current business models, in the organisational culture and in the management of top leadership, as well as in actions to implement Industry 4.0 technologies, specifically in initiatives with blockchain implementation to achieve traceability, increased security and optimisation of transactional processes.

From an academic perspective, this investigation is justified by the goal of seeking further knowledge about the use of blockchain technology for sustainable development the main academic. Its implications are the deepening of the use of blockchain technology in areas other than the financial services area and the creation of a visual overview of how blockchain technology can be used in institutions that wish to develop actions in the three areas of Sustainability.

1.4 Work limitation

The work was limited to analysing papers collected from the Web of Science and Science Direct databases that were selected according to a systematic literature review process using the strings blockchain, sustainability, and green. The refined search returned 33 papers from 2018 to 2021 that address the implementation of blockchain technology with positive results in some of the dimensions of sustainability.

As limitations of this paper, we mention the analysis of papers from two scientific papers and the incipient existing literature on the implementation of the blockchain in Sustainability actions, as it is a technology still used predominantly in the financial sector

2 Literature review

2.1 Blockchain

Esmaeilian (2018) argues that Industry 4.0 has the power to revolutionise corporate business models. According to Dantas et al. (2020), the concept of Industry 4.0 refers to the disruptive change in the industry's operating format, which starts to work in an intelligent, autonomous and interconnected way. The purpose of using these technologies is to make the industry more economical, efficient and connected to the internet.

Industry 4.0 is based on several innovative technologies, such as blockchain, Internet of Things (IoT), cyber-physical systems, additive manufacturing, artificial intelligence, big data, cloud computing, and augmented reality, among others. These technologies work to improve important points within the operation, such as flexibility, efficiency, productivity and increased competitiveness (Bai et al., 2020; Dantas et al., 2020).

Bai et al. (2020) point out another important contribution of Industry 4.0: it is capable of enhancing sustainability actions within companies, since traditional production systems usually have low environmental performance and low impact on solving social challenges.

The use of Industry 4.0 technologies can provide significant contributions to the three dimensions of sustainability. Regarding the economic benefits, mention is made of reduced costs, manufacturing time, delivery time, necessary labour, and waste and improved productivity, flexibility, and production customisation. From an environmental perspective, these technologies are expected to reduce energy consumption, waste, and residue emission and to aid in the control and tracking of greenhouse gas emissions, optimisation of delivery logistics in supply chains, and fostering of recycling and remanufacturing. Finally, in the social context, an autonomous and intelligent production environment is expected, in which these technologies will support the health and safety of employees (Bai et al., 2020).

In their research, Bai et al. (2020) found that blockchain and Mobile technologies show greater contributions in the economic dimension, while Sensing, Artificial Intelligence, Big Data and Cloud Computing show important impacts on the environmental dimension, and, finally, Cloud Computing and Big Data also impact the social dimension.

Schinckus (2020) reported that, after the 2008 global financial crisis, information asymmetry between financial institutions, investors and clients became evident, which generated pressure for increased transparency and for the inclusion of these players in financial processes. In this context, blockchain technology was first introduced by Santochi Nakamoto in 2008, in a system aimed at operationalising financial transactions through cryptocurrencies (Di Vaio and Varriale, 2020).

Bhushan et al. (2020) reported that this technology was initially designed for Bitcoin cryptocurrency transactions, with the purpose of facilitating direct digital transfer between players and eliminating intermediation. Bitcoin is known as a virtual currency used in international financial transactions without a centralised authority and its operation is supported by blockchain technology. (Esmaeilian et al., 2020; Schinckus, 2020)

Although blockchain technology was initially used as Bitcoin's transaction and cryptography system, its logic can be used in other sectors in addition to the financial system. Mention is made of potential application of this system in digital identity, electronic voting, and registration and transfer of properties, among others (Schinckus, 2020).

The blockchain programming structure is composed of four main elements, namely: data storage, consensus algorithm, smart contract, and decentralised application (Leng et al., 2020)

Saberi et al. (2019) explain that blockchain stores five basic characteristics of a transaction: its nature, quality, quantity, location, and property.

Unlike a traditional system, in which data are collected and stored on a central server, blockchain uses decentralised architecture for data analysis and storage. This architecture enables the automation, interaction and tracking of transactions without the need for a central authority (Kouhizadeh et al., 2021).

Blockchain is a technology based on a non-centralised and distributed ledger that can be applied to tangible and intangible assets. There is sharing on the digital network of information, the stage of verification of transactions, and the responsibility to ensure the integrity of the ledger (Andoni et al., 2019).

Transactions in this system occur and are validated by consensus and cryptography mechanisms. Once the transaction is validated by consensus by the other parts constituting the blockchain network, it will be stored in a block and receive a cryptographic hash function (CHF) and will later be linked to the previous existing blocks (Schinckus, 2020; Ahl et al., 2020)

From the moment a transaction is added to the block, it cannot be changed without previous transactions being edited and obtaining the consent of the digital network, which guarantees reliability and security to the system (Dutta et al., 2020).

In general, a transaction is understood as a compilation of data that represents the digital assets transferred between the players of the operation. The transaction is only included in a block after it has been validated by miners. In addition, in order to authenticate the transaction, blockchain uses asymmetric encryption mechanisms with digital signatures, which provides that each participant in the network uses a public key and a private key. The public key is used to decrypt, while the private key is used to encrypt (Bhushan et al., 2020).

Regarding the types of control and authentication mechanisms, blockchain systems can be categorised into public, private and consortium (Bhushan et al., 2020).

Public blockchain is an open structure that allows the participation of individuals regardless of their origin and entity. Each node in the network has autonomy to operate within the blockchain infrastructure and is responsible for collecting transaction data, carrying out the consensus validation and mining processes to achieve the rewards. On the other hand, private blockchain consists in an exclusive network with permission to access a determined group of people or companies. Thus, only a pre-selected individual or group performs data mining and validation procedures. Finally, consortium blockchain is usually found in the integration between private and public entities. In this case, a group of individuals is chosen to be responsible for the tasks of consensus and validation (Bhushan et al., 2020)

Blockchain architecture enables increased cyber security, transparency and accountability; provides auditability; eliminates the need for intermediation; obtains high resistance to data corruption attacks, product traceability and fraud prevention; and raises consumer confidence (Ahl et al., 2020; Di Vaio and Varriale, 2020).

Due the benefits achieved by implementing blockchain, there are examples of companies – such as Walmart, Maersk, Glencore and Provenance – that have implemented these systems in their supply chains to achieve improved operating performance, order tracking, and environmental protection and minimise product counterfeiting (Kouhizadeh et al., 2021).

Leng et al. (2020) argue that blockchain creates opportunities for innovation in business models and new ways to create, deliver and capture added value.

Blockchain is expected to be an appropriate solution for overcoming obstacles and improving operations in processes with transactions between individuals, governments, entities, and businesses or where proof of identity and property is required (Di Vaio and Varriale, 2020)

Leng et al. (2020) point out that due to the transparency and traceability of blockchain technology, it can be used to optimise manufacturing networks, work on sustainability actions, and select suppliers and partners that are capable of adding value.

Venkatesh et al. (2020) suggest that the implementation of blockchain to overcome challenges in the environmental dimension of sustainability is promising, as it will support the management and monitoring of sustainable actions. Kouhizadeh et al. (2019)

argue that blockchain can support the validation and measurement of information related to recycling program, reuse of materials, sustainable packaging, energy consumption, and carbon emissions.

2.2 Sustainability

If, on the one hand, corporate activities frequently harm the environment in some way, on the other hand they are responsible for meeting the needs of society. To maintain this balance, sustainability should be incorporated into the corporate strategy (Leng et al., 2020).

It is noted that sustainability is part of an institutional strategy that seeks to minimise risks and uncertainties in the operation and to optimise the use of resources and energy in a socially responsible manner, while meeting the demands of consumers and companies (Leng et al., 2020).

Esmaeilian et al. (2020) emphasise that the processes and products of the factories of the future must be designed so as to comprise aspects of sustainability, intelligence and security. The engagement with the execution of sustainability actions has intensified in the last decades due to the global commitment of private institutions and public authorities to improve waste management and reduce greenhouse gas emissions. There are even situations in which adherence to sustainable practices is a prerequisite for entering into commercial agreements, which accelerates the sustainable development of corporations (Dantas et al., 2020).

According to Kouhizadeh et al. (2021), sustainable actions in the companies' supply chain are closely linked to increased customer demand and retention. Some manufacturing models with sustainable processes were suggested by Leng et al. (2020), such as social manufacturing, open production, and collective manufacturing

There are social, competitiveness and regulatory factors that support the implementation of sustainable practices in supply chains. Consumers tend to seek information on the sustainability of the manufacturing of the goods they are purchasing, demand transparent and easily accessible platforms for checking information, and prefer companies that have certifications of sustainability actions for credibility (Kouhizadeh et al., 2021).

In the existing literature, sustainability is widely known by the term 'triple bottom line' and characterised by the three dimensions of social, economic and environmental development (Di Vaio and Varriale, 2020; Leng et al., 2020; Kouhizadeh et al., 2021).

Bhushan et al. (2020) describe that some authors have proposed adding other elements as pillars of sustainability, such as issues of infrastructure, governance, energy, climate change, pollution, waste and health.

The social conjuncture represents the reduction and/or elimination of the negative impacts caused by corporate activities on people's social life, health and quality of life. The economic perspective emphasises high operational performance and seeks a balance between resources used and goods provided. Finally, the environmental dimension focuses on the protection and preservation of natural resources (Di Vaio and Varriale, 2020).

According to Bai et al. (2020), companies are adopting sustainability actions to meet the demands of stakeholders and the expectations of society. In addition, Industry 4.0 technologies enable companies to develop in a sustainable manner and have potential to positively impact the 17 Sustainable Development Goals proposed by the United Nations, which are shown in Figure 1 (Lund et al., 2019).

Figure 1 Sustainable development goals (see online version for colours)

Source: United Nations (2021)

Schinckus (2020) states that the United Nations recognises that the application of blockchain can contribute to the achievement of the 17 Sustainable Development Goals through mechanisms to control corruption and operational deviations, develop infrastructure, empower communities, reduce fraud, increase food security, and track production chains and ecosystems, among other applications.

Bai et al. (2020) projected the applications and impacts of blockchain on the 17 Sustainable Development Goals, which are organised in Table 1.

Table 1 Intervention potential of Industry 4.0 technologies in relation to the sustainable development goals

Sustainable development goals		*Intervention potential of industry 4.0 technologies*
1	No poverty	Promote access to information, education,health care and opportunities for economic inclusion to end poverty.
2	Zero hunger and sustainable agriculture	Provide a sustainable farming environment and fair distribution systems to ensure adequate food security and nutrition and that there is no hunger anywhere.
3	Good health and well-being	Provide the digitalisation of health, which enables monitoring, prevention and creation of efficient health measures for the entire population according to their particularities.
4	Quality education	Create an accessible, fair and quality educational environment in primary and secondary education.
5	Gender equality	Provide an environment that will afford equal opportunities for success for men and women.
6	Clean water and sanitation	Support the provision of hygienic materials in any location at affordable prices, provide educational materials on hygienic practices and ensure access to clean water and sanitation by monitoring water and sewage parameters.
7	Affordable and clean energy	Foster the use of energy from renewable sources, increase energy efficiency and reduce prices for users.

Table 1 Intervention potential of Industry 4.0 technologies in relation to the sustainable development goals (continued)

Sustainable development goals		*Intervention potential of industry 4.0 technologies*
8	Decent work and economic growth	Create new business models to promote economic growth and create decent and rewarding jobs that have monitored working conditions.
9	Industry, innovation and infrastructure	Foster the emergence of new industries and information and communication systems optimized to provide an environment for innovation and infrastructure development.
10	Reduced inequality	Connect disconnected and marginalized citizens and reduce inequality in access to information and opportunities between countries and individuals.
11	Sustainable cities and communities	Build smart and sustainable cities and communities with public order, heritage and cultural security and sustainable living conditions.
12	Responsible consumption and production	Improve efficiency and transparency in supply chains and develop conscious and sustainable consumption patterns among consumers.
13	Climate action	Track carbon dioxide and greenhouse gas emissions and carbon footprint and consequently reduce the emission of these gases.
14	Life below water	Contribute to the sustainable use of ocean resources.
15	Life on land	Manage and monitor forests and biodiversity.
16	Peace, justice and strong institutions	Ensure an environment of freedom of expression, respect for human rights and a responsible and controlled institutional environment.
17	Partnerships for the goals	Facilitate the connection and collaboration between stakeholders carrying out sustainability actions

Source: Adapted from Bai et al. (2020)

According to Di Vaio and Varriale (2020), public policy agents must pay attention to the expected changes in the economic, social and environmental contexts through the use of Industry 4.0 technologies and use them as support to achieve the sustainable development goals. In addition, Di Vaio et al. (2020) proposes a framework for achieving Sustainable Development Goals through Sustainable Business Models, Artificial Intelligence and Knowledge Management Systems.

According to Saberi et al. (2019), for the adoption of blockchain in sustainable supply chains it will be necessary to circumvent external barriers, internal to the organisation, between different organisations and related to technological systems. These barriers can be seen in Table 2.

The intra-organisational barriers financial constraints, difficulty in changing organisational culture and lack of knowledge and expertise and inter-organisationl barriers as challenges in integrating sustainable practices and blockchain technology through SCM have a big impact on the implementation of blockchain in a company and its supply chain. If these barriers were circumvented, they would support the overcoming of other barriers such as Hesitation to convert to new systems, problems in collaboration and communication, access to technology and hesitation to adopt blockchain technology. (Saberi et al., 2019).

Table 2 Barriers of blockchain technology adoption in sustainable supply chain

Intra-organisational barriers	Financial constraints Lack of management commitment and support Lack of new organizational policies for using technology Lack of knowledge and expertise Difficulty in changing organizational culture Hesitation to convert to new systems Lack of tools for blockchain technology implementation in sustainable supply chains
Inter-organisational barriers	Lack of customer's awareness and tendency about sustainability and blockchain technology Problems in collaboration, communication and coordination in the supply chain Challenge of information disclosure policy between partners in the supply chain Challenges in integrating sustainable practices and blockchain technology through SCM Cultural differences of supply chain partners
Systems related barriers	Security challenge Access to technology Hesitation to adopt blockchain technology, due to negative public perception Immutability challenge of blockchain technology Immutability of technology
External barriers	Lack of governmental policies Market competition and uncertainly Lack of external stakeholders' involvement Lack of industry involvement in ethical and safe practices Lack of rewards and encouragement programs

Source: Adapted from Saberi et al. (2019)

3 Research method

According to Miguel (2010) and Turrioni and Mello (2012), this paper is characterised by its basic nature, exploratory purpose and qualitative approach. The investigation procedure is a systematic literature review aimed at analysing the practices for implementing blockchain technologies in institutions, which impacted the economic, social and environmental aspects of sustainability.

3.1 Methodological procedure

Kitchenham (2004) and Miguel (2010) state that the methodological procedure of systematic literature review is capable of collecting, analysing and discussing data with the purpose of raising questions and developing scientific knowledge. Due to the big number of research, the literature review method is used often (Massaro et al., 2016).

In this work, a systematic review was chosen, as the objective is to evaluate in the literature the examples of blockchain implementation that corroborate the conduct of actions linked to the three dimensions of sustainability.

Siegel et al. (2019) organises the systematic review into ten stages, which are: definition of the research objective and purpose; development of the research protocol; definition of relevance criteria; research and collection of papers; selection of studies; evaluation of the quality and relevance of the studies; data extraction; data synthesis; paper writing and dissemination. The research protocol adopted in this work is based on the model proposed by Siegel et al. (2019) and is shown in Table 3.

In addition, it was realised by the CENPRO research group that the paper by Huillca and Ignacio (2020) could aggregate with this study, because it works with the implementation of blockchain technology in wastewater transformation and that impacts the goal Clean water and sanitation of the Sustainable Development Goals. This paper demonstrates the advantage of using a decentralised network with blockchain technology, as it achieves a state of reliability and traceability of transactions carried out in this environment and promotes a secure and transparent environment for conducting public bids and auctions.

The final selection of papers of this systematic literature review was composed of 34 documents.

4 Development and findings

The results of the systematic literature review, the refinement of the reading of titles, abstracts and texts and complementation of the research group are shown in Table 4.

Table 3 Research protocol adopted in this paper

Process	*Development of the process in this research*
Definition of research objective and purpose	Determination of how blockchain can impact institutional actions relevant to the economic, social and environmental elements of sustainability
Development of the research protocol	The papers were collected from the Web of Science and Science Direct databases using the strings "blockchain AND sustainability AND green"
Definition of relevance criteria	We sought examples of blockchain implementation in economic, social and environmental actions within institutions
Research and collection of papers	Search in the Web of Science and Science Direct databases using the strings "blockchain AND sustainability AND green"
Selection of papers	Reading of titles and abstracts to trace whether the work addressed the use of blockchain in actions of any of the dimensions of sustainability
Evaluation of the quality and relevance of papers	Full reading of papers that showed relevance
Data extraction	Data extraction and compilation regarding examples of blockchain implementation with impacts on the institution's economic, environmental and social areas
Summary of the data	Summarisation of the data in tables
Paper writing	Insertion of data into the body of the paper

Source: Adapted from Siegel et al. (2019)

Table 4 Refinement of the systematic literature review

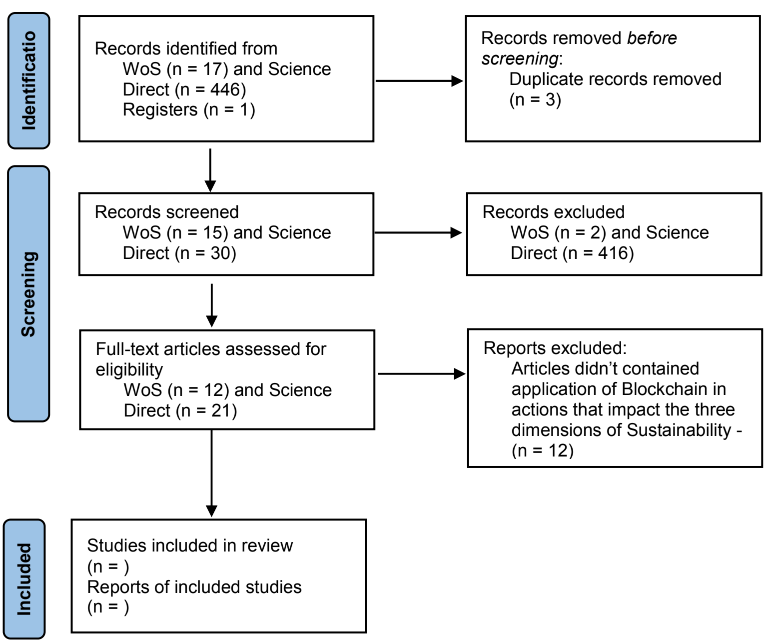
Database	*Web of science*	*Science direct*	*CENPRO group*
Initial number of documents	17	446	
Number of documents chosen for full reading	15	30	
Number of repeated documents	3		
Number of refined documents	12	21	
Papers found out by the research group			1
Final number of selected documents	34		

Source: Prepared by the author

As suggested by Del Giudice et al. (2021) this flow is exposed in Figure 2 using PRISMA.

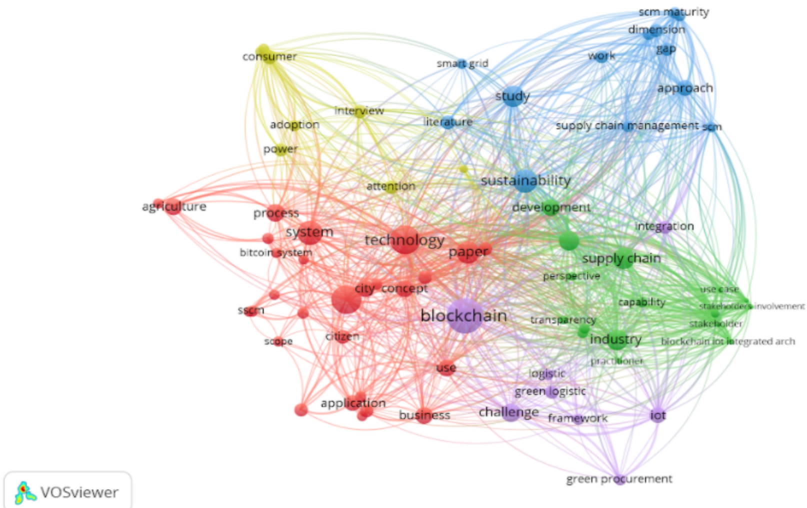
We conducted analysis as to the prominence and relationship between the keywords of the papers surveyed in the Web of Science database using the Vosviewer software. In this analysis, the appearance of the keywords at least three times in different papers was used as a criterion. Figure 3 shows that the most prominent and repetitive words are blockchain, technology, sustainability, system, supply chain, paper, industry and challenge.

Figure 2 PRISMA flow diagram (see online version for colours)



Source: Adapted from Page et al. (2020)

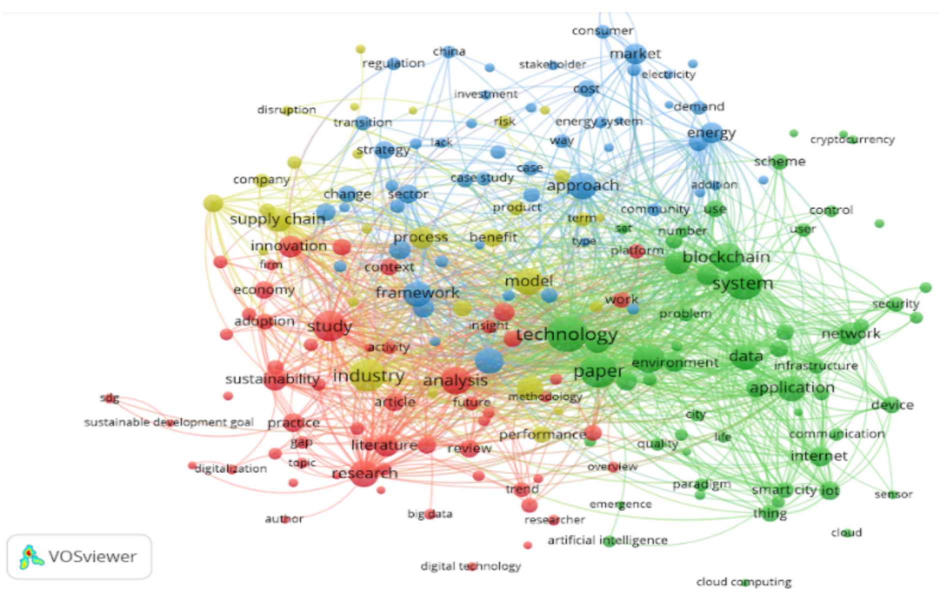
Figure 3 List and prominence of keywords generated by the Vosviewer software from the papers collected in the web of science database (see online version for colours)



Source: Prepared by the author

When performing the same analysis of prominence of keywords of the papers surveyed in the Science Direct database by the Vosviewer software, the criterion implemented was the appearance of the keywords in at least fifteen different papers. Figure 4 shows that the words with most prominence and more repetitions are technology, paper, industry, framework, model, supply chain, blockchain, system, approach and application.

Figure 4 List and prominence of keywords generated by the Vosviewer software from the papers collected in the science direct database (see online version for colours)



Source: Prepared by the author

Table 5 present the 34 papers refined in the systematic literature review, with their corresponding blockchain's application and notes on the impact of the use of blockchain technology on the economic, environmental and social dimensions of sustainability.

Table 5 Mention in the papers of the impacts of blockchain technology on the three dimensions of sustainability

Authors	*Blockchain application*	*Economic*	*Environmental*	*Social*
Ahad et al. (2020)	Monitoring the environmental conditions of smart cities		X	
Ahl et al. (2019)	Provide the creation of business models that do not require intermediary agents Fostering the purchase of energy from renewable generation sources Tracking greenhouse gas emissions Fostering the increase of renewable energy generators Income generation for citizens due to new business models Changing consumer behaviour patterns with the appreciation of sustainable products and companies	X	X	X
Ahl et al. (2020)	Energy trade directly between producers and consumers Fostering new investment models, such as crowdfunding Monitoring of environmental conditions in smart cities	X	X	
Andoni et al. (2019)	Energy trade directly between producers and consumers Fostering the purchase of energy from renewable generation sources Provide information to auditors Integration of small-scale renewable energy with distribution Identity Management	X	X	X
Balzarova and Cohen (2020)	Product lifecycle management Provide eco-labelling. Deforestation Monitoring climate change monitoring Biome degradation monitoring	X	X	
Bhushan et al. (2020)	Fostering smart cities Sharing and storing patient data in healthcare Feasibility of autonomous and interconnected transport systems Energy trading directly between producers and consumers Optimisation of customs clearance Product tracking and authenticity Provide information for audits Feasibility of financial transfers directly between interested parties	X		

Table 5 Mention in the papers of the impacts of blockchain technology on the three dimensions of sustainability (continued)

Authors	*Blockchain application*	*Economic*	*Environmental*	*Social*
Choi and Luo (2019)	Management of the fashion supply chain Demand forecast management More accurate demand planning with rational use of resources	X	X	
Dantas et al. (2020)	Solid waste management Tracking greenhouse gas emissions Changing consumer behaviour patterns with the appreciation of sustainable products and companies Fostering a culture of sharing goods		X	X
Dhungana and Bulut (2020)	Power sharing on mobile networks Double auction promotion to regulate the price and quantity of electricity	X		
Di Vaio and Varriale (2020)	Provide information for audits Airport supply chain management: aircraft, boarding control, security and customs clearance Product lifecycle management	X		
Dutta et al. (2020)	Feasibility of financial transfers directly between interested parties Granting credit through smart contracts Tax Payment Monitoring Product tracking and authenticity Optimisation of rental business models through smart contracts Fostering the purchase of energy from renewable generation sources Authentication of recyclers Reverse Logistics Monitoring Traceability of scientific content and research. Enabling electronic voting	X	X	X
Esmaeilian et al. (2020)	Product lifecycle management Process optimisation Monitoring and tracking of sustainable performance	X	X	
França et al. (2020)	Direct payment in local businesses without the need for intermediaries Solid waste management Monitoring the correct disposal of waste Productive and financial inclusion of citizens through the use of social currency Financial reward for recycling jobs Income generation for citizens due to new business models Tracking life quality indicators	X	X	X
Huillca and Ignacio (2020)	Implementation of Blockchain technology in wastewater transformation and that impacts the goal Clean water and sanitation		X	

Table 5 Mention in the papers of the impacts of blockchain technology on the three dimensions of sustainability (continued)

Authors	*Blockchain application*	*Economic*	*Environmental*	*Social*
Kouhizadeh and Sarkis (2018)	Removal of intermediaries from operations Development of suppliers through smart contracts Integration of warehouse information Expanding and facilitating crowdsourcing and crowdshipping Product lifecycle management Provide information to auditors Tracking of sustainability actions Foster shared logistics Tracking greenhouse gas emissions Tracking Recycling Materials Fostering the purchase of energy from renewable generation sources	X	X	
Kouhizadeh et al. (2021)	Product lifecycle management Fostering the purchase of energy from renewable generation sources Carbon credit trading management Tracking greenhouse gas emissions Food safety monitoring Public administration tracking Storing and Sharing Patient Health Records	X	X	X
Kouhizadeh et al. (2019)	Circular economy Monetisation of waste and disposal and income generation Tracking Recycling Materials Fostering the reuse of discarded materials Fostering the purchase of energy from renewable generation sources Reverse Logistics Monitoring Carbon Credit Trading Management Income generation for citizens due to new business models Changing consumer behaviour patterns with the appreciation of sustainable products and companies	X	X	X
Kumar et al. (2020)	Tracking and authenticity of e-commerce products, food, luxury and agricultural products	X		
Lahkani et al. (2020)	E-commerce management and optimisation Inventory management	X		
Leng et al. (2020)	Product lifecycle management	X		
Llacuna (2020)	Circular economy Monitoring the environmental conditions of smart cities Energy efficiency monitoring Enabling self-management of the population of the local public administration	X	X	X

Table 5 Mention in the papers of the impacts of blockchain technology on the three dimensions of sustainability (continued)

Authors	*Blockchain application*	*Economic*	*Environmental*	*Social*
Lund et al. (2019)	Product and order tracking Decrease in the sale and distribution of illegal products Fostering the purchase of energy from renewable generation sources Tracking greenhouse gas emissions Reduction of hunger and food vulnerability due to waste reduction	X	X	X
Nayak and Dhaigude (2019)	Optimising the property transfer process Provide information for certifications Fostering the purchase of energy from renewable generation sources Authentication of sustainable products Tracking Recycling Materials Carbon Credit Trading Management Tracking human rights compliance Tracking Fair and Safe Work Practices	X	X	X
Oliveira et al. (2020)	Manage electric vehicle charging stations from different generators Provide payment methods for the purchase of energy at charging stations Urban mobility and public transport chain management	X		
Oliveira et al. (2020)	Granting credit through smart contracts Payments in intelligent transport systems Reverse Logistics and shared logistics Storing and Sharing Patient Health Records Authentication of diplomas and certificates Preservation of intangible and cultural heritage Promoting e-governance and increasing citizen participation in government decisions	X	X	X
Pumphrey et al. (2020)	Energy trade directly between producers and consumers Fostering the purchase of energy from renewable generation sources	X	X	
Saberi et al. (2019)	Access to product history information Tracking greenhouse gas emissions Carbon Credit Trading Management Monitoring and tracking of sustainable performance Fostering the purchase of energy from closer generation sources Authentication of sustainable products Management of sustainable behaviour reward programs Tracking human rights compliance Tracking Fair and Safe Work Practices	X	X	X

Table 5 Mention in the papers of the impacts of blockchain technology on the three dimensions of sustainability (continued)

Authors	*Blockchain application*	*Economic*	*Environmental*	*Social*
Schinckus (2020)	Optimising the property transfer process Product tracking and authenticity Carbon Credit Trading Management Fostering the purchase of energy from renewable generation sources Fostering financing for climate actions water resources management identity management Enabling electronic voting Food safety monitoring	X	X	X
Schulz et al. (2020)	Promotion of financing for climate action projects Carbon Credit Trading Management Tracking greenhouse gas emissions Identification of fraudulent activities of environmental criteria identity management Management and implementation of social welfare and income transfer programs		X	X
Singh et al. (2020)	Intelligent transport systems and autonomous vehicle network Optimisation of energy use in smart cities Storing and Sharing Patient Health Records	X	X	X
Souza et al. (2019)	Energy trading directly between producers and consumers	X		
Sun and Zhang (2020)	Public administration tracking			X
Tan et al. (2020)	Logistical tracking Optimisation of vehicle routes Sharing network traffic Planting and harvesting tracking Encouraging the direct sale of goods without the need for an intermediary Shared logistics Optimisation of vehicle routes Tracking Fair and Safe Work Practices	X	X	X
Venkatesh et al. (2020)	Sustainable performance monitoring and tracking Tracking Fair and Safe Work Practices Storing and Sharing Patient Health Records		X	X

Source: Prepared by the author

Table 6 summarise the references of authors in the systematic review who mentioned potential positive impacts of blockchain on the economic dimension of sustainability. The potential associated with the economic aspect was categorised into the classes supply chain, certifications, energy, mobility, business, administrative processing and taxation.

It is shown the main potential benefits of applying blockchain technology to the economic aspect of sustainability, such as supply chain integration and tracking, providing information for decision-making and auditing processes, managing urban mobility, stimulating the circular economy, encouraging direct sales between actors without the need for intermediation, direct energy trade between generators and consumers, optimisation of property transfer processes, among others.

Assessing Sustainable Development Goals achieved by using blockchain technology with economic impacts, it listed the targets affordable and clean energy, decent work and economic growth, industry, innovation and infrastructure, sustainable cities and communities, responsible consumption and production and peace, justice and strong institutions.

Table 7 summarise the potential impacts of blockchain on the environmental dimension of sustainability according to authors in the systematic review.

Table 6 Potential impact of blockchain on the economic dimension of sustainability according to authors in the systematic review

Category	*Sustainable development goals*	*Potential economic impact*	*Authors*
Supply chain	9 – Industry, Innovation and Infrastructure	Supply chain information integration	Nayak and Dhaigude (2019), Saberi et al. (2019) and Choi and Luo (2019)
		Product lifecycle management	Esmaeilian et al. (2020), Kouhizadeh and Sarkis (2018, 2021), Di Vaio and Varriale (2020), Leng et al. (2020) and Balzarova and Cohen (2020)
		Supplier development	Kouhizadeh and Sarkis (2018) and Lund et al. (2019)
		Product tracking and combating the sale of illegal products	Saberi et al. (2019), Tan et al. (2020), Bhushan et al. (2020), Schinckus (2020), Kumar et al. (2020) and Dutta et al. (2020)
		Stock management	Kouhizadeh and Sarkis (2018) and Lahkani et al. (2020)
		Expansion of crowdsourcing and crowdshipping	Kouhizadeh and Sarkis (2018)
	12 – Responsible Consumption and Production	Product history information	Saberi et al. (2019);
Certifications	12 – Responsible Consumption and Production	Certification information	Nayak and Dhaigude (2019)
		Audit information	Di Vaio and Varriale (2020) and Bhushan et al. (2020)
Administrative Processing	9 – Industry, Innovation and Infrastructure	Optimisation of the property transfer process	Nayak and Dhaigude (2019) and Schinckus (2020)
		Optimisation of customs clearance	Bhushan et al. (2020)

Table 6 Potential impact of blockchain on the economic dimension of sustainability according to authors in the systematic review (continued)

Category	*Sustainable development goals*	*Potential economic impact*	*Authors*
Taxation	16 – Peace, Justice and Strong Institutions	Monitoring of tax payments	Dutta et al. (2020)
Energy	7 – Affordable and Clean Energy	Direct energy trade between producers and consumers	Pumphrey et al. (2020), Ahl et al. (2020), Souza et al. (2019), Bhushan et al. (2020) and Andoni et al. (2019)
		Providing means of payment at recharging stations	Oliveira et al. (2020)
Energy	7 – Affordable and Clean Energy	Energy sharing in mobile networks	Dhungana and Bulut (2020)
		Double energy price and quantity auction promotion	Dhungana and Bulut (2020)
	11 – Sustainable Cities and Communities	Management of electric vehicle recharging stations	Oliveira et al. (2020)
Mobility	9 – Industry, Innovation and Infrastructure	Airport management	Di Vaio and Varriale (2020)
	11 – Sustainable Cities and Communities	Management of urban mobility and public transport chain	Oliveira et al. (2020)
		Vehicle route optimisation	Tan et al. (2020)
		Network traffic sharing	Tan et al. (2020)
		Intelligent transport systems and autonomous vehicle network	Oliveira et al. (2020), Singh et al. (2020) and Bhushan et al. (2020)
Business	8 – Decent Work and Economic Growth	Stimulating circular economy	Kouhizadeh et al. (2019) and Llacuna (2020)
		Credit granting through smart contracts	Oliveira et al. (2020) and Dutta et al. (2020)
		Enabling direct financial transfers between the parties	Bhushan et al. (2020) and Dutta et al. (2020)
		Encouraging direct sale without the need for an intermediary	Kouhizadeh and Sarkis (2018), Tan et al. (2020), Lahkani et al. (2020) and Ahl et al. (2019)
		Direct payment at local shops without intermediation	França et al. (2020)

Source: Prepared by the author

Potential environmental impacts were categorised into the supply chain, corporate performance, energy, environment, administrative processing, and recycling groups.

The potential positive impacts on the environmental dimension due to blockchain implementation are management of water and solid resources, monitoring of environmental indicators, stimulating sustainable consumption, tracking of greenhouse gas emissions, management of trade in carbon credits, shared and reverse logistics, authentication of sustainable products, among others.

Table 7 Potential impact of blockchain on the environmental dimension of sustainability according to authors in the systematic review

Category	*Sustainable development goals*	*Potential environmental impact*	*Authors*
Supply chain	9 – Industry, Innovation and Infrastructure	Shared logistics	Kouhizadeh and Sarkis (2018), Tan et al. (2020) and Oliveira et al. (2020)
	11 – Sustainable Cities and Communities	Vehicle route optimisation	Tan et al. (2020)
	12 – Responsible Consumption and Production	Reverse logistic	Kouhizadeh et al. (2019), Oliveira et al. (2020) and Dutta et al. (2020)
		Providing ecolabelling	Balzarova and Cohen (2020)
Recycling	12 – Responsible Consumption and Production	Tracking recycling materials	Nayak and Dhaigude (2019), Kouhizadeh and Sarkis (2018) and Kouhizadeh et al. (2019)
		Authentication of recyclers	Saberi et al. (2019) and Dutta et al. (2020)
Corporate performance	9 – Industry, Innovation and Infrastructure	Accurate demand planning	Choi and Luo (2019)
	12 – Responsible Consumption and Production	Tracking sustainability actions	Kouhizadeh and Sarkis (2018)
		Encouraging sustainable consumption	Esmaeilian et al. (2020) and Nayak and Dhaigude (2019)
		Management of sustainable behaviour reward programs	Saberi et al. (2019)
		Sustainable performance monitoring and tracking	Esmaeilian et al. (2020), Saberi et al. (2019), Ahl et al. (2020) and Venkatesh et al. (2020)
		Monitoring of waste disposal	França et al. (2020) and Ahl et al. (2020)
	13 – Climate Action	Greenhouse gas emissions tracking	Kouhizadeh and Sarkis (2018), Lund et al. (2019), Saberi et al. (2019), Ahl et al. (2019, 2020), Dantas et al. (2020), Schulz et al. (2020) and Kouhizadeh et al. (2021)

Table 7 Potential impact of blockchain on the environmental dimension of sustainability according to authors in the systematic review (continued)

Category	*Sustainable development goals*	*Potential environmental impact*	*Authors*
Administrative processing	12 – Responsible Consumption and Production	Authentication of sustainable products	Nayak and Dhaigude (2019)
		Provide information for audits	Kouhizadeh and Sarkis (2018) and Andoni et al. (2019)
		Tracing fraudulent activities as to environmental criteria	Schulz et al. (2020)
Energy	7 – Affordable and Clean Energy	Fostering energy purchase from renewable generation sources	Nayak and Dhaigude (2019), Kouhizadeh and Sarkis (2018), Kouhizadeh et al. (2019, 2021), Lund et al. (2019), Saberi et al. (2019), Pumphrey et al. (2020), Ahl et al. (2019, 2020), Schinckus (2020), Dutta et al. (2020) and Andoni et al. (2019)
		Integration of small scale renewable sources with the distribution grid	Andoni et al. (2019)
		Fostering energy generation by decentralized and renewable sources	Ahl et al. (2019)
		Monitoring of energy efficiency	Llacuna (2020)
	11 – Sustainable Cities and Communities	Optimisation of energy use in smart cities	Singh et al. (2020)
Environment	6 – Clean water and sanitation	Wastewater transformation monitoring	Huillca and Ignacio (2020)
	11 – Sustainable Cities and Communities	Monitoring of environmental conditions of smart cities	Llacuna (2020) and Ahad et al. (2020)
	12 – Responsible Consumption and Production	Solid waste management	França et al. (2020) and Dantas et al. (2020)
	13 – Climate Action	Climate change monitoring	Balzarova and Cohen (2020)
		Fostering financing for climate actions	Schinckus (2020) and Schulz et al. (2020)
		Carbon credit trade management	Nayak and Dhaigude (2019), Kouhizadeh et al. (2019, 2021), Saberi et al. (2019), Ahl et al. (2020), Schinckus (2020) and Schulz et al. (2020)
	14 – Life below Water	Water resource management	Schinckus (2020)
	15 – Life on Land	Deforestation monitoring	Balzarova and Cohen (2020)

Source: Prepared by the author

Thus, the aims Affordable and Clean Energy, Industry, Innovation and Infrastructure, Sustainable Cities and Communities, Responsible Consumption and Production, Climate Action, Life below Water, Clean water and Sanitation and Life on Land were observed that can be attained with blockchain in the environmental dimension of sustainability.

Finally, Table 8 present the potential impacts of blockchain on the social dimension of sustainability, according to authors in the systematic literature review.

Table 8 Potential impact of blockchain on the social dimension of sustainability according to authors in the systematic review

Category	*Sustainable development goals*	*Potential social impact*	*Authors*
Public administration	16 – Peace, Justice and Strong Institutions	Monitoring of public administration	Kouhizadeh et al. (2021) and Sun and Zhang (2020)
		Enabling self-management of local public administration	Llacuna (2020)
		Promotion of e-governance and increased participation of the population in decisions	Oliveira et al. (2020)
		Enabling electronic voting	Schinckus (2020)
Food	2 – Zero Hunger and Sustainable Agriculture	Food security	Schinckus (2020) and Kouhizadeh et al. (2021)
		Reduction in hunger and food vulnerability	Lund et al. (2019)
Consumption	12 – Responsible Consumption and Production	Changing consumption patterns with valuation of sustainable products	Kouhizadeh et al. (2019), Dantas et al. (2020) and Ahl et al. (2019)
Income generation	8 – Decent Work and Economic Growth	Income generation due to new business models	Kouhizadeh et al. (2019), França et al. (2020) and Ahl et al. (2019)
		Financial reward for recycling jobs	França et al. (2020)
Administrative processing	16 – Peace, Justice and Strong Institutions	Identity management	Schinckus (2020), Schulz et al. (2020) and Andoni et al. (2019)
		Authentication of diplomas and certificates	Oliveira et al. (2020)
		Scientific research traceability	Dutta et al. (2020)
		Preservation of intangible and cultural heritage	Oliveira et al. (2020)
Quality of life	3 – Good Health and Well-being	Tracking of quality of life indicators	França et al. (2020)

Table 8 Potential impact of blockchain on the social dimension of sustainability according to authors in the systematic review (continued)

Category	*Sustainable development goals*	*Potential social impact*	*Authors*
Inequality reduction	10 – Reduced Inequality	Management and implementation of social cash transfer programs	Schulz et al. (2020)
		Productive and financial inclusion of citizens by social currency	França et al. (2020)
Health	3 – Good Health and Well-being	Patient medical record storage and sharing	Oliveira et al. (2020), Venkatesh et al. (2020), Singh et al. (2020) and Kouhizadeh et al. (2021)
Labour	8 – Decent Work and Economic Growth	Tracking fair and safe labour practices	Nayak and Dhaigude (2019), Saberi et al. (2019), Tan et al. (2020) and Venkatesh et al. (2020)
		Human rights compliance tracking	Nayak and Dhaigude (2019) and Saberi et al. (2019)

Source: Prepared by the author

The categories used to classify potential social impacts are: public administration, food, consumption, income generation, administrative processing, quality of life, inequality reduction, health, and labour.

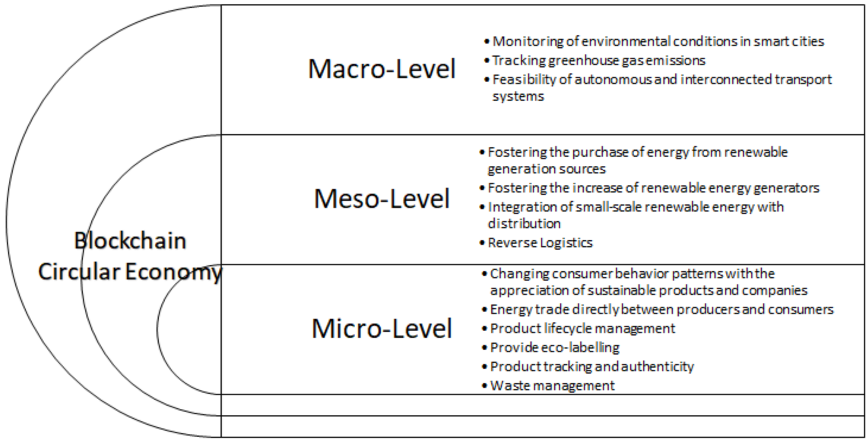
Regarding the third line of sustainability, which concerns social developments, it was found that blockchain technology can help in solving problems related to food security, reduction in food wasting and hunger, tracking fair labour practices, tracking compliance with human rights, tracking public administration and the possibility of self-management by the population, income generation through the creation of new business models, management and implementation of cash transfer programs, among others.

Lastly, the objectives Zero Hunger and Sustainable Agriculture, Good Health and Well-being, Decent Work and Economic Growth, Reduced Inequality, Responsible Consumption and Production and Peace, Justice and Strong Institutions were noticed as potentially reached by the use of blockchain technology.

According to Papageorgiou et al. (2021), the circular economy can be implemented in three stages: the micro-level the meso-level and the macro-level. Based on the potential positive impacts of the blockchain on circular economy and sustainability actions, it has been suggested the following conceptual framework.

Through the analysis of Figure 5, this framework suggests that as the blockchain technology evolves in the DLT (Distributed Ledger Technology), there is a systemic and generalised impact on different levels of the circular economy, due to its ability to improve traceability, monitoring, information sharing, credibility, speed and no need for transactions' intermediation.

Figure 5 A conceptual framework of blockchain technology, circular economy and sustainable action relationships



Source: Prepared by the author

5 Related studies

Dutta et al. (2020) address the opportunities and challenges of blockchain in supply chain operations and identified positive potentials in the three aspects of Sustainability, with use in identity management, product authentication, authentication of good production practices and waste disposal, monitoring of reverse logistics, circular economy and protection of democratic principles through increased security of elections

The papers by Ahl et al. (2019) and Andoni et al. (2019) address the implementation of the blockchain in the energy sector and bring developments in the use of technology in the three dimensions of Sustainability, such as through the creation of new business models, new sources of revenue, integration of small generators, tracking of the generation process sustainable energy and provide a reliable energy purchase and sale environment without the need for intermediaries.

França et al. (2020) focused on the use of the blockchain in waste management, which also has the potential to impact the three aspects of sustainability, through the productive and financial inclusion of citizens who recycle waste and support in the management and monitoring of the correct disposal of solid waste.

6 Discussion

We noted that administrative processing is the only common category for the economic, environmental, and social dimensions of sustainability. In addition, the supply chain and energy categories are common for the economic and environmental dimensions of sustainability.

We observed that the greatest number of examples and the most significant impacts for corporate performance are found in the economic and environmental dimensions, while the results from the implementation of this technology in the social aspect are closer to the reality of governance and public management.

Otherwise, the targets No Poverty, Quality Education, Gender Equality and Partnerships for the Goals were not observed in the elements found in the systematic literature review made in this paper.

There are some barriers to the implementation of blockchain technology in support of sustainable development due to factors such as the high cost and long time to develop the technology, the need for technology adoption by stakeholders in the chain, high energy consumption, long processing time, and shortage of technology experts.

In addition to enable the execution of several sustainability actions, blockchain technology is used in conjunction with other tools of Industry 4.0, such as Internet of Things (IoT), Artificial Intelligence, Additive Manufacturing, Big Data, and Cyber-Physical Systems, which becomes an obstacle to its implementation itself due to the increased complexity of these technologies.

This observation underscores the importance of industry 4.0 technologies, in particular blockchain technology, becoming accessible and being able to meet all of humanity's needs and contribute to the achievement of Sustainable Development Goals.

Once the main barriers to use of blockchain are the high time and high cost of development, but the commitment to achieving the UN's 2030 agenda is latent and urgent, some alternatives for enabling blockchain in sustainability actions are sponsorship, sharing of development technology or patent break.

Regarding the perspective for technology adoption, an integrated action of global private and public leaders is suggested in order to guarantee the implementation of the blockchain by stakeholders in their chains

On the other hand, a negative point of using blockchain technology in sustainability issues is that public blockchain systems usually demand high consensus from several points in the chain, which causes high energy consumption. The efficiency's increasing of this technology is fundamental for blockchain to consolidate itself as a green supply chain technology. Thus, through the proposed conceptual framework to overcome the gap of blockchain's application on Sustainable Actions and Circular Economy, it is observed that the blockchain has potential to support the consolidation of Circular Economy, once the barriers of access to technology, high cost and resistance to use are overcome.

Finally, the tools created by blockchain technology must be accessible and easy to use, otherwise this may result in a lack of incentive for use by consumers.

In order to complement the outcomes of this research, it is suggested that new papers from other databases that address the theme of sustainability and blockchain be mapped and accessed, in order to validate the results found in this work.

7 Conclusions

The investigation through systematic literature review indicates evidence that blockchain technology has potential to support the conduct of actions in the three dimensions of sustainability – economic, environmental and social – and support the achievement of the Sustainable Development Goals proposed by the United Nations.

In the economic dimension, examples of benefits were found in the areas of supply chain, product and process information, mobility, financial transfers, energy, and property transfer.

While in the environmental dimension, the initiatives are linked to the monitoring and measurement of environmental indicators, credibility for audits, reverse and shared logistics, recycling, and renewable energy sources.

Finally, the mentioned benefits in the social aspect are: hunger reduction by reducing waste, food security, monitoring of labour practices and conditions, tracking and participation in the public administration, income generation, and identity management.

From the perspective of achieving the individual goals of the Sustainable Development Goals, it was observed that blockchain has a positive performance potential in most of the goals, with the exception of the elements No Poverty, Quality Education, Gender Equality and Partnerships for the Goals which were not observed in the literature review.

It is important that blockchain technology may be tested and validated in sectors other than the financial sector, as the benefits of traceability, monitoring, sharing and credibility can add to different types of operations.

From the specific perspective of Sustainability, it is suggested that the focus of blockchain development in sustainable actions should be directed mainly to guarantee access to technology and solve the main barriers as lack of rewards and encouragement programs, challenges in integrating sustainable practices and blockchain technology through SCM, financial constraints, lack of knowledge and expertise and lack of tools for blockchain technology implementation in sustainable supply chains.

If these obstacles are overcome, it is expected that the blockchain will contribute to achieving the Sustainable Development Goals and consolidating the circular economy.

These gaps are guiding points for future studies in investigations regarding sustainability and the use of blockchain technology to support sustainable development.

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