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RESEARCH ARTICLE

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Is blockchain able to enhance environmental sustainability? A systematic review and research agenda from the perspective of Sustainable Development Goals (SDGs)

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Abstract

Blockchain is a disruptive technology that is revolutionizing information technology and represents a change of cultural paradigm for the way in which information is shared. Companies are rushing to understand how they can use blockchain distributed ledger technology to innovate processes, products and transactions. In a globalized world where environmental sustainability is a critical success factor, what is the role of the blockchain? By using a systematic review approach and the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) protocol, this study attempts to identify whether and how blockchain technology is considered able to affect environmental sustainability. Findings from 195 studies from 2015 to 2020 were analysed after the search protocol was applied. The results indicate that blockchain technology could contribute to environmentally sustainable development goals (SDGs) from different points of view, such as supporting the realization of a sustainable supply chain, improving energy efficiency and promoting the creation of secure and reliable smart cities. Furthermore, the investigation highlights the sectors where to focus research investments, providing a way to reward sustainable behaviour and increasing environmental sustainability. On the other hand, blockchain has no negligible negative effects on the environment that need to be considered before adoption.

KEYWORDS

bibliometric analysis, blockchain, digitalization, Sustainable Development Goals, sustainability, technology

1 | INTRODUCTION

The Fourth Industrial Revolution is characterized by a whole transformation of our society, changing our way of production and giving opportunities to change our lives; nevertheless, there is an increasing awareness that this transformation needs to take into account the necessity to create a more environmentally sustainable society. Accordingly, recent studies focus on the integration of Industry 4.0 technologies and corporate sustainability (Dubey et al., 2017), considering that the principles and practices of Industry 4.0 will unlock the full potential of sustainable organizations, moving towards a more

Abbreviations: PRISMA, Preferred Reporting Items for Systematic Review and Meta-Analyses; SDGs, Sustainable Development Goals.

sustainable society as well as world-class sustainable manufacturing (Dubey et al., 2015; Dubey et al., 2016). This is possible because, at the macrolevel, the development of technology is related to a country's sustainability (Gouvea et al., 2018), and environment-based technical progress can stimulate improvements in environmental quality (Song & Wang, 2016). At the microlevel, the new industrial paradigm can be an important step forward towards more sustainable industrial value creation: the allocation of resources—products, materials, energy and water—may be realized in a more efficient way based on intelligent cross-linked value creation modules (Stock & Seliger, 2016). Moreover, Industry 4.0 tools have recently been considered to potentially further environmental sustainability decisions since they enable a better strategic alignment between the employed information technologies and the organizational goals (de Sousa Jabbour et al., 2018). Scholars have begun to examine the effect of Industry 4.0 technologies on environmental sustainability, usually with a focus on specific topics such as sustainability manufacturing or supply chain management (de Sousa Jabbour et al., 2018; Ford & Despeisse, 2016; Jin et al., 2017; Kumar et al., 2018; Luthra & Mangla, 2018; Stock & Seliger, 2016). Nevertheless, while existing studies are largely focused on the positive effect of the new paradigm, it is also important to underline that some innovations may impose unpredictable costs on society, and their transformative nature may render it difficult to anticipate their overall effect once diffused (Binder & Witt, 2011; Mulgan, 2016). Accordingly, our paper tries to explore the relationship between Industry 4.0 and environmental sustainability focusing specifically on blockchain technology, which is often considered one of the most remarkable innovations in the 21st century. Blockchain is defined as 'a novel and fast-evolving approach to recording and sharing data across multiple data stores (or ledgers). This technology allows for transactions and data to be recorded, shared, and synchronized across a distributed network of different network participants' (World Bank, 2007).

Blockchain is now applied in a variety of fields (Centobelli et al., 2021), and many governments have used this latter technology to enhance environmental sustainability (Glavanits, 2020).

Blockchain technology can indeed facilitate new means of green production, the monitoring and storage of data-related activities responsible for pollution and environmental degradation and the real-time collection and analysis of green or low carbon data for timely decision making. Blockchain can also favour the development of a green supply chain (Bai & Sarkis, 2019; Mora et al., 2021; Saberi et al., 2019).

Although both empirical evidence and previous studies have shown how economic and environmental sustainability can be improved with blockchain technology (Pazaitis et al., 2017; Varsei et al., 2014), the existing literature is fragmented and often focused on a specific aspect, such as the green supply chain (Varriale et al., 2020) or city management (Mora et al., 2021). Moreover, many existing studies have analysed the link between blockchain and sustainable development without focusing specifically on environmental issues (Mora et al., 2021). Finally, while scholars have emphasized the positive effect of blockchain, less attention has been given to the environmental challenges derived by this technology adoption. For example, traditional blockchain systems require the use of a large amount of energy, creating consequently negative effects on the natural environment; moreover, the host of big servers requires bulky buildings that can have a negative impact on the landscape.

To reduce this literary gap, our paper aims to investigate in detail the complex relationship between blockchain adoption and the natural environment. To explore the different dimensions of environmental sustainability, we use the framework of sustainable development goals (SDGs) developed by the United Nations in 2015. The SDGs are positioned as a blueprint and shared agenda for future peace and prosperity for the planet and its population. The 17 SDGs emphasize the ending of poverty and other deprivations in alignment with strategies to improve health and education, reduce inequality, develop economic growth while tackling climate change and preserving our forests and oceans (UN, 2018). Companies of any size or production specialization can develop more responsible business models, giving a decisive boost to the implementation of SDGs through investments in technological innovation and multipartnership involvement (Di Vaio et al., 2020). From the set of SDGs, we selected those connected to the different dimensions of environmental sustainability. Our aim is to develop a comprehensive map that analyses the two-bin effects of blockchain on environmental-related SDGs. In contrast to previous studies, we also take into account the negative effects of blockchain implementation, and we do not focus on a specific topic (such as supply chain) but analyse the use of blockchain to explore its implementation at different levels. To make our analysis robust, we use a systematic review approach and the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) protocol, and all the papers published in both management and technical journals that analyse the relationship between blockchain and the natural environment have been analysed. Then, a content analysis of the papers was developed, identifying a set of keywords linked to each SDG that helped us code the presence of specific references to SDG goals in each paper.

After this first analysis, we evaluate whether each paper considers a positive effect of this technology implementation on environmental sustainability (i.e., reduction of energy losses, reduction of CO_2 emissions and land protection) or not (increase of energy consumption and growth of waste amount). At the end of the analysis, a complete map of the effects, both positive and negative, of blockchain technologies on the environment was drawn, considering all the environmental sustainability dimensions. In this regard, our paper contributes to the literature on new technology adoption and environmental sustainability because we systematize the trajectories of the existing studies and emphasize the areas not already explored (e.g., we observe that while some SDGs are largely cited, others are almost neglected by the studies). Moreover, our paper has practical implications because it sheds light on the complex relationship between blockchain adoption and the environment, giving both managers and policy makers a useful decision tool. In fact, the present investigation highlights the sectors where to focus research investments, providing a way to reward sustainable behaviour and increase environmental sustainability.

The remainder of the paper is structured as follows. After the Introduction, Section 2 explains the relationship between blockchain and environmental sustainability; Section 3 analyses the methodology and data collection process; Section 4 presents the results of the bibliometric analysis; Section 5 deals with the analysis of research trends based on co-occurrence analysis; Section 6 summarizes the relationships between blockchain and SDGs. Finally, Section 7 reports the conclusions and implications of this research.

2 | BLOCKCHAIN AND ENVIRONMENTAL SUSTAINABILITY

Blockchain technology works in the form of a distributed ledger system where data, used in communication or transactions, are stored in a publicly available network of digital blocks (Moll & Yigitbasioglu, 2019). Each of these blocks contains a digital signature and timestamp, which renders the individual blocks virtually immutable (Kokina et al., 2017; Nakamoto, 2008). The digital blocks are arranged together following a complex mathematical logic—a process called 'hashing' (Nakamoto, 2008)—to form a chain of blocks, hence the name blockchain (Angelis and da Silva, 2019; Harris & Wonglimpiyarat, 2019). Blockchain applications are being developed according to a peer-to-peer logic in which organizations can exchange goods, services and information without the need of central bodies to verify identity, validate transactions or enforce commitments or at least by removing the need of many intermediaries as it happens today. At a first level, this may enable gains in efficiency and lowering of costs for firms and other organizations by allowing for faster transactions that are disseminated and synchronized digitally across a number of different but fewer parties (Davidson et al., 2016).

The most notable application of blockchain is in the development and operation of cryptocurrencies (e.g., Bitcoin, Ethereum, among others). In addition to the financial services industry, blockchain is also considered in other sectors, such as international trade, taxation, supply chain management, business operations and governance (Kimani et al., 2020; Pólvora et al., 2020). In a recent review of blockchain studies in the management field, Centobelli et al. (2021) show that researchers have exploited the benefits of blockchain information technologies in several domains (e.g., supply chain management, security and privacy, edge computing, artificial intelligence and consortium blockchain). Although blockchain is still in its nascent stage (see Ahluwalia et al., 2020), scholars agree that this technology offers several prospective benefits that will assist organizations in meeting the demands of the Fourth Industrial Revolution (Dai & Vasarhelyi, 2017; Moll & Yigitbasioglu, 2019; Nakashima et al., 2018; Singh et al., 2019). Lee (2019, p. 781) also predicts that blockchain will significantly alter, if not replace, many of the current accounting and finance applications, thus heralding a 'completely new industrial infrastructure'. Blockchain's appeal derives from its ability to support transparent data sharing, optimization of business processes, reduction of operating costs, improvement in collaborative efficiency and development of a system that does not need explicit incorporation of trust in its control, as in the case of supply chains, for instance (Francisco & Swanson, 2018). Among the other advantages, blockchain can address a range of environmental sustainability challenges, supporting environmental sustainability through three key underlying mechanisms relating to resource rights, product origins and behavioural incentives (Herweijer et al., 2018; Hughes et al., 2019). It could facilitate new means of green production, as well as monitoring and storing data-related activities responsible for pollution and environmental degradation, real-time collection and analysis of green or low carbon data for timely decision making and favouring the development of a green supply chain (Bai & Sarkis, 2019; Saberi et al., 2019). Recently, Varriale et al. (2020) reviewed 30 papers that link blockchain to the supply chain and affirmed that this latter technology can support the creation of sustainable environmental supply chain monitoring and reduce CO_2 emissions along the supply chain, monitoring the exchange of dangerous waste and creating a system of incentives favouring recycling, improving circular economy practices and monitoring the use of natural resources, especially in the agri-food industry.

Moreover, Glavanits (2020) also shows that not only scholars but also governments have recognized the potential of blockchain to act positively on SDGs. With specific regard to environmental SDGs, the author cites the example of California that has used blockchain to monitor and oversee the groundwater of Sacramento or the Share & Charge project applied first in the United Kingdom and then in the EU that promotes the use of blockchain to monitor the charging system of electric cars.

Recently, Mora et al. (2021) emphasize the role of blockchain in creating a sustainable society, describing how different blockchain digital solutions can support sustainability from three points of view according to the subject to which the technology can be oriented: service delivery, resource management and city administration.

The first two groups of proposals are directly related to social development challenges, and the third collects proposals to address social issues at the municipal level since the city is the most important ecosystem where citizens live and where technology is already playing a key role. This latter paper does not directly address the topic of environmental sustainability, but using the SDG framework, it gives some examples of how blockchain can address some environmental issues, especially using cryptocurrency as a reward system in the area of waste and water management or using smart contracts and platforms to manage energy transactions or CO_2 emissions. Nevertheless, this latter contribution, not implementing a scientific methodology, is mainly descriptive, and by focusing on city managers, it gives only a partial description of how blockchain can affect the environmental SDGs. Moreover, although the authors have recognized that blockchain can also exert a negative impact on society, they do not explore in detail this latter issue.

Despite these positive benefits, blockchain-adopting organizations must typically deal not only with high development and implementation costs and risks but also with various technical, managerial and ethical concerns (Bai & Sarkis, 2017). Some of these concerns are specifically related to environmental and sustainability dimensions, including, for example, the amount of energy required for key algorithms, processing and computations within the blockchain (Saberi et al., 2018; Truby, 2018), and complex implementation issues, especially in implementation with wide scope.

Our work starts from this literary gap to explore the two-bin effects of blockchain on environmental SDGs in a more comprehensive manner and adopts a strong methodology.

3 | RESEARCH METHODOLOGY

In this section, the research methodological approach is explained and defined. Figure 1 depicts the logical scheme underlying the methodological approach of this study. As shown in Figure 1, we first define the *data set identification*. We chose to use the Scopus database because it is the largest abstract and citation database of peer-reviewed literature, and it is largely used by scholars worldwide. Then, we decided to use PRISMA as a systematic review protocol describing the rationale, hypothesis and planned methods of the review (Cioffi et al., 2020; Shamseer et al., 2015). The application of the PRISMA protocol has helped us to create a dataset of papers. Subsequently, *content-based* research was conducted to analyse the content of the papers and identify the main bibliographic information of the papers and the relationships to SDGs. In addition, the data were stratified and analysed in the *data processing* through the use of Microsoft Excel and VOSviewer software (Meng et al., 2020). Data processing helps us to identify three kinds of findings. First, we create a bibliometric analysis of the studies that link blockchain and environmental sustainability (publication by years and citations, contribution by journals, country analysis and so on). Then, we define the research trends and thematic areas through a *co-occurrence analysis of the keywords*. Third, we define a matrix that identifies the relationship between blockchain and SDGs.

A detailed description of the research analysis and results is provided in the following sections.

3.1 | The PRISMA protocol

To understand the relevant trend of study on blockchain, we conducted a systematic literature review adopting a consolidated approach, the PRISMA Protocol (Moher et al., 2015). The PRISMA statement is used in several disciplines to help authors improve systematic reviews and meta-analyses. In particular, similar to any systematic literature review, the PRISMA statement is an iterative process and consists of a 27-item checklist (Moher et al., 2009, 2015). It also provides a flow diagram that supports practitioners in the identification, screening, eligibility and inclusion steps of the systematic literature review process. The primary purpose of this method is to plan, identify and evaluate studies to extract and synthesize data from the literature (Tranfield et al., 2003), ensuring the objectivity, transparency and replicability of bibliographic research. The reason for the selection of this protocol among other standards and guidelines that explicitly address how literature reviews should be reported and structured (Snyder, 2019) is that it has a methodological and analytic approach

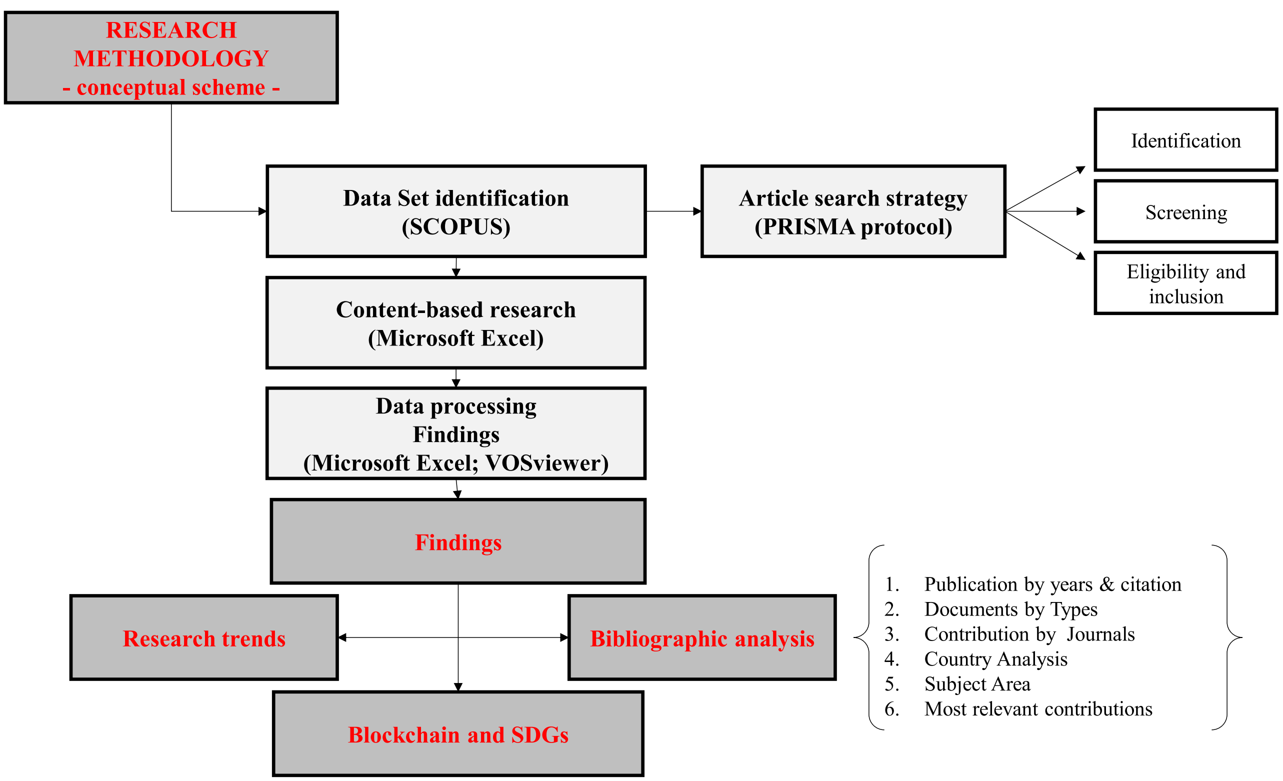

FIGURE 1 Research methodology—conceptual scheme [Colour figure can be viewed at wileyonlinelibrary.com]

that is quite clear and easy to understand (Moher et al., 2015). Moreover, this methodology was recently adopted by scholars for systematic review or meta-analysis to investigate analogous topics (i.e., Buer et al., 2018; Macke & Genari, 2019; Magon et al., 2018; Mardani et al., 2020). This protocol was administered as shown in Figure 2.

3.1.1 | Identification

The *first step* of the protocol is to define how to identify and select papers that have to be included in the review. We sourced the articles constructing a search query from SCOPUS because this database provides a comprehensive portfolio of scientific journals, as it is widely used in academic research (Álvarez Jaramillo et al., 2019; Macke & Genari, 2019). We identified a set of keywords that we searched in keywords, titles or abstracts of the papers. We limited our research to specific document types, such as articles or reviews, excluding, that is, book chapters, editorials or notes and the source type to the scientific journal, excluding conference proceedings or books based on the fact that peer-reviewed academic journal articles are normally considered to be at the frontier of knowledge compared to these other sources.

The search string comprises two parts: the first set of words limited the results to the theme of environmental sustainability, while the second expression limited the results to blockchain technology.

- Search String: (TITLE-ABS-KEY (green) OR TITLE-ABS-KEY ("circular economy") OR TITLE-ABS-KEY (carbon) OR TITLE-ABS-KEY (sustainab*) OR TITLE-ABS-KEY (climate) OR TITLE-ABS-KEY (co2) OR TITLE-ABS-KEY ("ecol*") OR TITLE-ABS-KEY (emission*) OR TITLE-ABS-KEY ("natural environment*") OR TITLE-ABS-KEY (footprint) AND TITLE-ABS-KEY (cryptocurrency) OR TITLE-ABS-KEY (blockchain) OR TITLE-ABS-KEY (bitcoin)

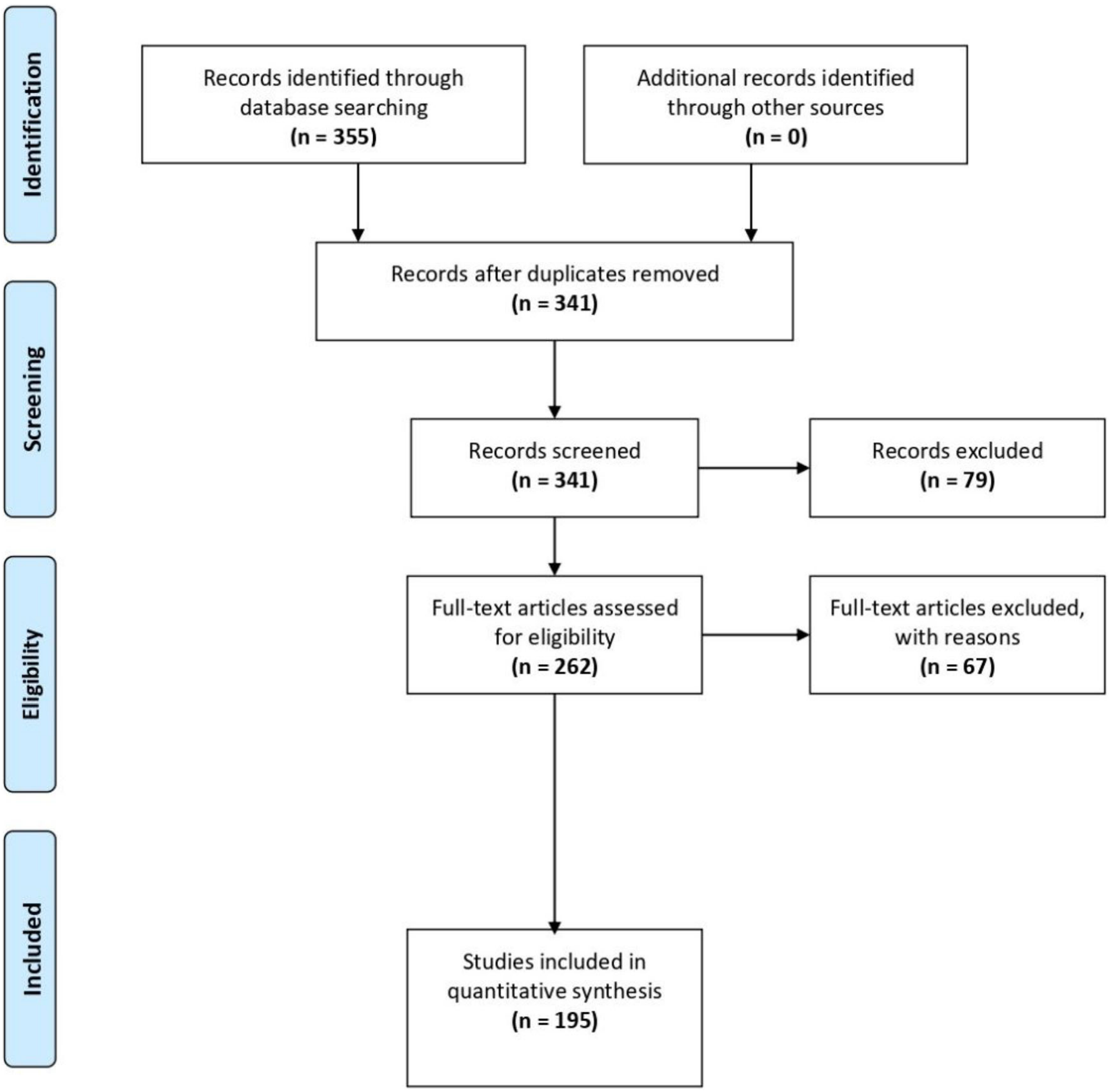

FIGURE 2 The review process, according to the PRISMA guidelines (Moher et al., 2009) [Colour figure can be viewed at wileyonlinelibrary.com]

We did not include limits to the time span of the research. The initial search process generated 355 academic papers from 2015 (the year where the first document was published) to 2020 (investigation period).

3.1.2 | Screening

The *second step* of the PRISMA statement involves the definition of raw criteria to screen the collected selection of papers. This screening activity was performed by reading the abstract or keywords of the papers and allowed us to exclude 79 papers. Exclusion criteria were identified and are summarized as follows:

E1: Documents not related to Blockchain (papers off topic),
E2: Documents not in English,
E3: Duplicate documents and
E4: Documents not published in peer-reviewed international journals.

3.1.3 | Eligibility and inclusion

The *last steps (third and fourth)* of the review process according to PRISMA guidelines regard the definition of criteria for eligibility and the inclusion of papers in the final sample. We assessed the fit of each paper that satisfied the eligibility criteria, which was verified after carefully reading and reviewing all full-text articles. In particular, we included in the final sample only papers that address environmental-related SDGs preliminarily identified among the 17 different goals that all the United Nations Member States adopted since 2015 as a universal call to action to fulfil the ambitious targets by 2030. In particular, among the 17 SDG targets defined by the UN, we selected those that can be directly or indirectly linked to environmental sustainability, namely, SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 9 (Industry Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), SDG 14 (Life Below Water) and SDG 15 (Forests, Desertification and Biodiversity). Thus, during this step, we excluded all the papers that seemed to be on topic but referred to other SDGs that were not specifically environmentally related (i.e., no poverty or zero hungry). The overall search process resulted in a sample of 195 bibliographic records (hereinafter 'bibliographic sample'). Thus, eligibility and inclusion criteria were identified and are summarized as follows:

EI1: Documents in the context of blockchain related to environmental SDGs.

3.2 | Content-based analysis

All the relevant information of the bibliographic sample, such as the title, abstract, keywords, authors' names and affiliations, journal name, year of publication and number of citations of the identified records, was exported to an MS Excel spreadsheet. The dataset is integrated with other information based on the review objectives to support the overall coding process. In particular, we selected a set of dimensions and options that allowed us to classify the *195 selected articles* (see Table 1). The first set of dimensions is related to the nature of the article and the geographic and industry scope of each of them. The second set of dimensions is related to our main objective, namely, the

TABLE 1 Framework for the content-based analysis

Investigated aspect	Dimension	Option	Option definition and criteria for selection
Methodological approach	Approach	Theoretical/empirical approach	The paper provides a theoretic argumentation, model and simulation or provides empirical application, survey or validation.
Geography	Reference to the country of the corresponding authors	Specific country/comparison/ regional	The paper is authored by scholars located in a single country or in a geographic region.
Industry	Reference to specific industry	Specific industry/generic	The paper is set on specific industry.
Environmental-related SDGs	Reference to the SDG	Environmental-related SDGs considered or not	The paper addresses the specific environmental-related SDG (please see Appendix A) and blockchain technology.
	Direction of the effects	Positive/negative	The paper clearly addresses that blockchain technology has a positive or negative effect on the specific environmental-related SDGs.
	Main topic of the paper	Main topic/not main topic	The effect of blockchain technology on environmental-related SDGs is the main topic of the paper.

research of direct or indirect reference of blockchain technologies effect on environmental-related SDGs. We then developed a list of keywords that helped us code the presence of specific references to SDG goals in each paper (see Appendix A). The creation of this list has been necessary because each SDG goal definition is wide and covers several features not considered in the specific title of the SDG itself. Specifically, we identify if a paper recalls directly or indirectly a specific SDG, putting the value 1 or 0 otherwise. Each paper can make reference to more than one SDG. To understand and review the direction of the effect of blockchain technology implementation on environmental-related SDGs, we evaluate whether each paper considers a positive effect of this technology implementation on environmental sustainability (i.e., reduction of energy losses, reduction of CO_2 emissions and land protection) or not (increase of energy consumption and growth of waste amount), using a dummy variable (value 1 for a positive effect; 0 otherwise). Third, we identify whether the SDGs mentioned in the paper represent the main topic of the paper (value 1 of our coding) or not (value 0).

3.3 | Data processing method

Bibliographic coupling and co-occurrence analysis were performed using VOSviewer software (Biggi & Giuliani, 2020). VOSviewer (http://www.vosviewer.com) has been used to construct bibliometric networks (Van Eck & Waltman, 2010). Items (i.e., the objects of interest) in the networks have been connected by co-authorship, co-occurrence, citation, bibliographic coupling or cocitation links. To construct a network, bibliographic database files (i.e., Scopus) have been provided as input to VOSviewer. VOSviewer has been developed in the Java programming language. Items have been grouped into clusters. Networks can be constructed for different units of analysis. In this study, fractional counting was used (Van Eck & Waltman, 2009). The idea of fractional counting is to reduce the influence of documents with many authors. When fractional counting is used, the strength of a co-authorship link between two authors is determined not only by the number of documents co-authored by the authors but also by the total number of authors of each of the co-authored documents (Waltman & Van Eck, 2015). In the case of fractional counting, when an author has co-authored a document with n other authors, this yields a strength of $1/n$ for each of the n co-authorship links. The total strength of the n co-authorship links then equals 1. This is different from the full counting case, in which each of the n co-authorship links has a strength of 1, resulting in a total strength of the n co-authorship links of n (Zhao & Strotmann, 2011).

4 | BIBLIOGRAPHIC ANALYSIS

The 195 papers selected are descriptively analysed in this section with respect to the year of publication, journal, field of study, country, citations, methodological approach with the aim of identifying challenges and future trends within the selected documents. The analysis of the papers has been focused on papers published only in international journals.

4.1 | Publication by years and citation

The analysis of documents by type pointed out the following distribution: articles that were not open access (92; 47.2%) and articles that were open access (103; 52.8%). Furthermore, the analysis showed that the highest percentage of published papers is in the last 3 years, according to the following distribution: 2020 (88; 45%), 2019 (58; 29.7) and 2018 (34; 17.4%). This result is not surprising, as we expected; between 2018 and 2020, interest in this topic is growing significantly due to political interest in blockchain and environmental issues. In addition, the analysis pointed out that (naturally) the most cited papers were those of 2019 (44.4%), 2018 (44.3%) and 2017 (27.3%). In 2017, the percentage of citations would seem to be a bug because a greater value would be expected. In 2017, only 12 papers were published but were not cited in following years. Figure 3 shows the distribution of the group of papers as a function of the publication year and citations. An interesting aspect is that application papers were published with good continuity since 2018.

4.2 | Documents by types

After a very careful and scrupulous analysis of each paper, the 195 papers were classified into two types: empirical (43%) and theoretical (57%), as shown in Table 2. In addition, documents were classified by qualitative approach (65%) and quantitative approach (35%), as shown in Table 3.

The majority of papers employ case study analysis (22.1%) or illustrate conceptual frameworks (16.9%); other methodologies used in the selected studies are literature reviews (9.2%) or simulation models (4.6%).

Figure 4 shows that the trend of empirical papers has changed during the years; at the beginning (2015), the papers are only theoretical, while in 2020, the number of theoretical and empirical papers became almost similar.

4.3 | Contribution by journals

Figure 5 shows the bibliographic coupling distribution by journals. The minimum number of documents of a source considered is 5. Of all the sources, nine meet threshold. For each of the nine sources, the total strength of the bibliographic coupling links with other sources is calculated. Of course, the sources with the greatest total link are selected.

Table 4 shows the scores and ranking of the top 10 most cited journals. More specifically, the following data were analysed: documents, citations, SCImago Journal Rank (SJR), CiteScore and Source Normalized Impact (SNIP). It is important to emphasize that SJR

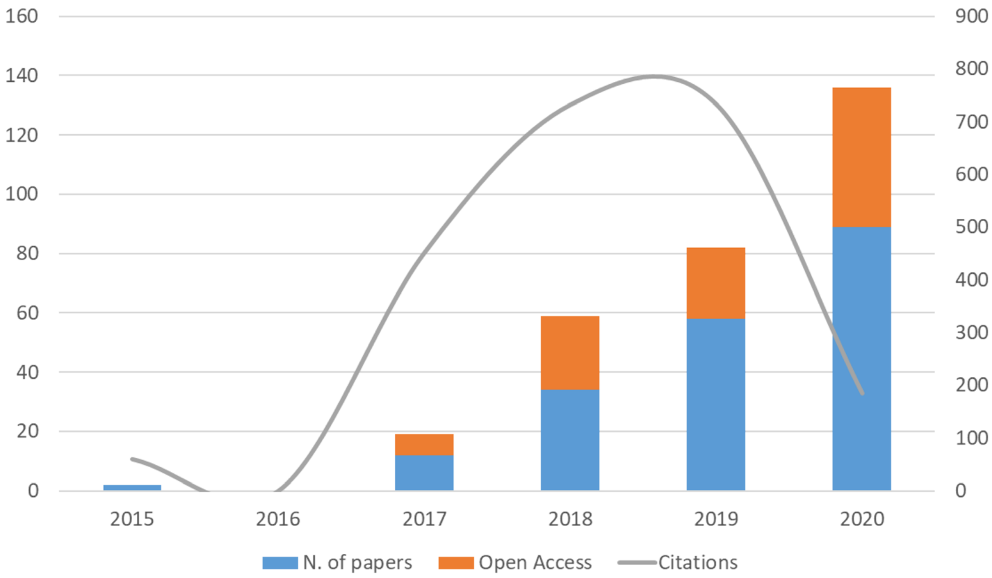

FIGURE 3 Time distribution of publications and type of publications and citations [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Documents by types (empirical and theoretical)

	No. of papers	%
Empirical	83	43
Theoretical	112	57
Total	195	100.0

TABLE 3 Documents by approach (qualitative and quantitative)

	No. of papers	%
Qualitative	54	65
Quantitative	29	35
Total	195	100.0

measures weighted citations received by the serial. Citation weighting depends on the subject field and prestige of the citing serial; CiteScore measures average citations received per document published in the serial; and SNIP measures actual citations received relative to citations expected for the serial's subject field. The ranking shows that all journals belong to high-quality journals. This means that the topic under study is very prominent and is of interest to major editors and publishers.

4.4 | Country analysis

To understand the world trend in the 'blockchain' phenomenon, an in-depth analysis of the interest of the different countries has been developed. It is certainly difficult to allocate each paper to a country or a continent. In fact, many papers are the result of international collaboration with authors from different countries. However, it is possible to emphasize that considering the distribution of papers by nationality of the corresponding author, it emerges that, globally, the most active countries are China (24%) and the United States (16%). In Europe, the United Kingdom (13%) is among the top 10, as shown in Figure 6.

It is evident that the foremost country is China. In fact, China has undertaken many projects in the field of blockchain. For example, the China Securities Regulatory Commission (CSRC) recently received an application to list an exchange-traded fund (ETF) that will track blockchain-related stocks as underlying assets. The application of blockchain technology to regulatory trials in the country's regional equity markets, according to China Banking News, will be on 22 October. Blockchain is gaining momentum in China because it is considered a unique way to solve the challenges of financial inclusion and cross-border remittances (Hou et al., 2018). In other words, China aims to use blockchain to encourage data sharing, to make businesses more efficient and to establish better credit systems in various sectors, including the Internet of Things (IoT), supply chain management and government services. Even in the United States, blockchain is no longer considered only a useful tool for obtaining new cryptocurrencies or managing databases. The United States has recognized the growth potential of using this technology in public service delivery, and many of them are already at high levels of implementation (Bakarich et al., 2020). Ohio, for example, is the first US state to accept Bitcoin for tax payments. However, for the blockchain to emerge definitively as a 'technological imperative', which the public administration cannot ignore, the states will have to change the existing regulations.

4.5 | Subject area

Figure 7 shows the analysis of papers by subject area. The analysis pointed out that as the blockchain is a 'set' of technologies, this implies that the subject areas are different and varied. In any case, it is possible to outline a trend of the subject area most treated in the

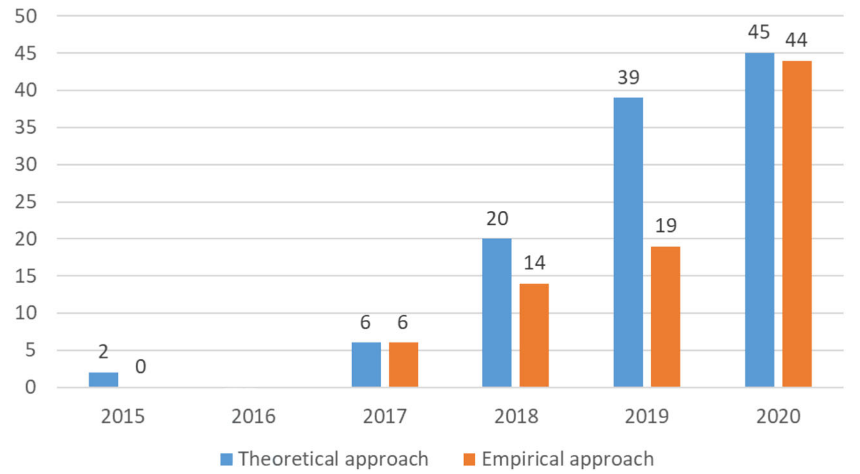

FIGURE 4 Methodological trends [Colour figure can be viewed at wileyonlinelibrary.com]

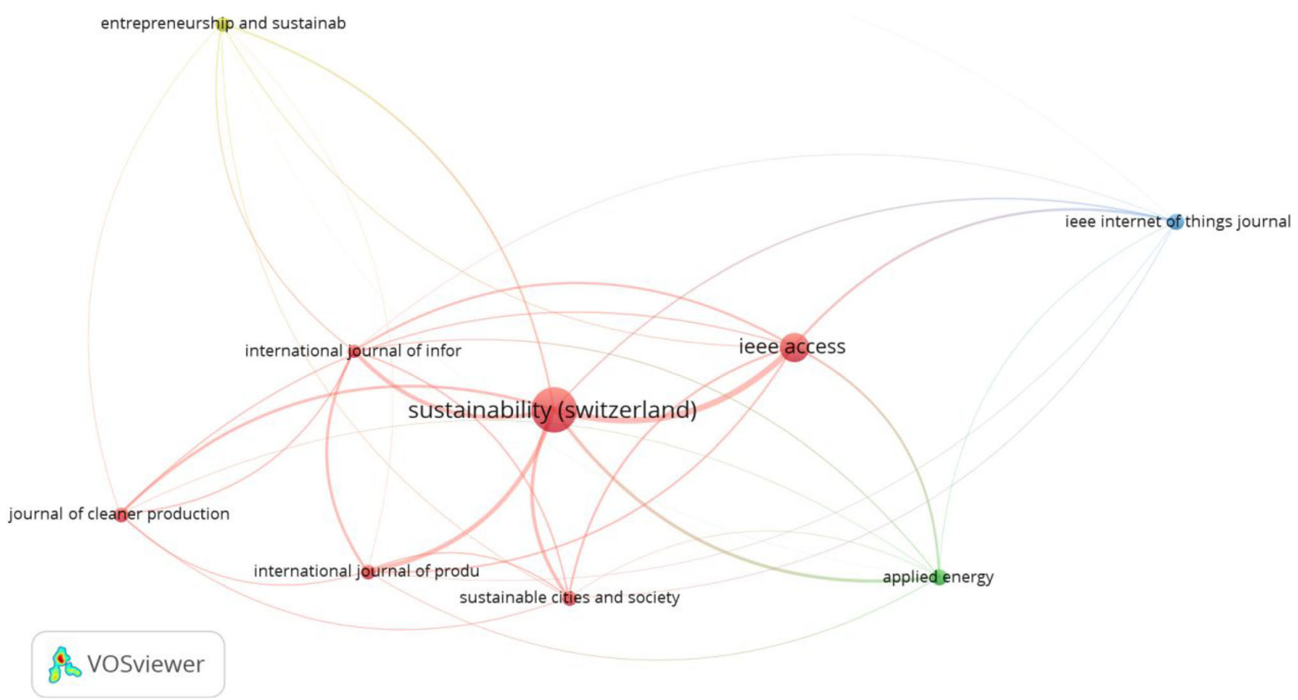

FIGURE 5 Contribution by journals (VOSviewer) [Colour figure can be viewed at wileyonlinelibrary.com]

scientific community. In particular, the most productive areas are Engineering (17.0%), Computer Science (15%) and Social Sciences (13%). It is remarkable to note that immediately after the most productive area is Environmental Science (11.0%).

4.6 | Industry analysis

Moreover, a deeper analysis of the paper content show that many work focus their analysis on the application of the blockchain in particular industrial sectors. The most representative sectors is energy and utilities (17.3%). A complete detail is shown in the Table 5.

The representativeness of the industries are probably due to the choice of industrial big players. In particular, according to the sectors outlined in Table 5, it is interesting to note that the most famous companies in the world are experimenting with new business models and technology solutions based on blockchain. For example, in the *logistics and supply chain* sector, IBM and Unilever collaborate to create a blockchain solution to simplify Unilever's supply chain and provide more transparency to increase the relationship of trust with consumers (Venkatesh et al., 2020). Regarding the *agriculture/agri-food* sector, IBM is also developing a food safety blockchain program with Walmart, which allows monitoring each of the steps to which the food has been subjected through a Q-code on the label. In the *transportation (airport/maritime)* sector, the shipper Maersk is developing TradeLens, which aims to automate logistical flows by eliminating the bottlenecks that generate enormous waste (Thiraviya Suyambu et al., 2020). The motivation of the project is based on the awareness

TABLE 4 Scores and ranking of the top 10 most cited journals (source Scopus)

Source	Publisher	Documents[a]	Citations[a]	SJR[b]	CiteScore[b, c]	SNIP[b]
Sustainability (Switzerland)	Multidisciplinary Digital Publishing Institute (MDPI)	51	435	0.581	3.2	1.165
IEEE Access	IEEE	22	409	0.775	3.9	1.734
International Journal of Information Management	Elsevier	5	246	2.881	14.1	3.773
International Journal of Production Research	Taylor & Francis	6	345	1.776	7.6	2.075
Sustainable cities and society	Elsevier	6	67	1.356	7.5	1.987
Applied energy	Elsevier	7	130	3.607	16.4	2.865
Journal of Cleaner Production	Elsevier	6	13	1.886	10.9	2.394
IEEE Internet of Things Journal	IEEE	7	70	2.607	12.6	4.110
Entrepreneurship and Sustainability Issues	Entrepreneurship and Sustainability Center	6	24	1.171	7.0	5.681

[a]Sourced by VOSviewer.
[b]Sourced by SCOPUS.
[c]Calculated on 6 May 2020 (last update).

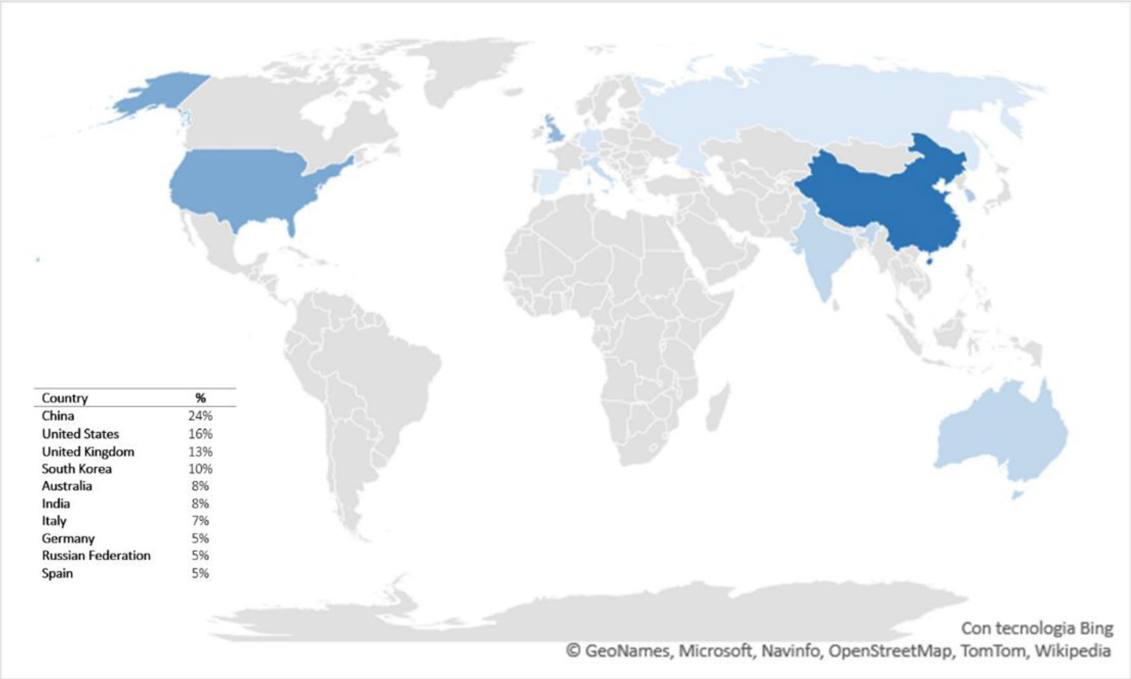

FIGURE 6 Paper distribution per country (top 10 country) [Colour figure can be viewed at wileyonlinelibrary.com]

that each year, 80% of all goods in common use are sent by sea, which has a total value of four trillion dollars. Document management is estimated to affect transport costs by 15% to 20% and up to 50% on particular routes, such as New York–Amsterdam. TradeLens eliminates this waste thanks to data management via blockchain. Finally, an equally interesting project is the KodakCoin project, developed by Kodak. It is a blockchain and cryptocurrency-based service that allows photographers to store and licence their photos directly from their blockchain (Corbet et al., 2020).

4.7 | Most relevant contributions

Table 6 shows the most relevant contributions analysed according to two parameters: number of Citations in Scopus and Field-Weighted Citation Impact (FWCI), sourced from SciVal. The first parameter is well known; it denotes the number of documents that have cited the article, while the FWCI shows how well cited an article is when compared to similar documents. A value greater than 1.00 means that the document is more cited than expected according to the average. It

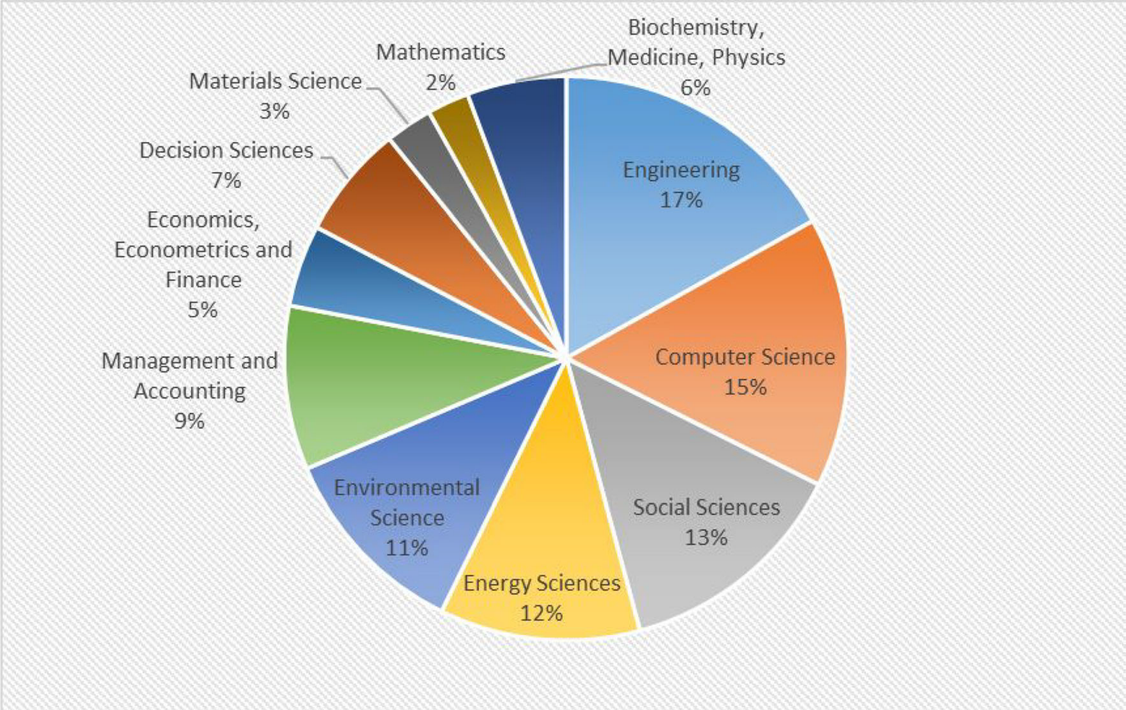

FIGURE 7 Subject area [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 5 Sectors

Sectors	%
Agriculture/agri-food	8.7
Carbon market	3.1
Energy and utilities	17.3
Fashion	2.1
Fintech/cryptocurrency	8.2
Fish and forest	1.0
Healthcare	0.5
ICT	2.1
Logistics and supply chain	11.8
Manufacturing/industry	7.2
Mining	3.6
Miscellaneous	14.3
Services	1.5
Sustainable business model	16.5
Transportation (air/maritime)	2.1
Total	100.0

takes into account the year of publication, the document type and the disciplines associated with its source. The FWCI is the ratio of the document's citations to the average number of citations received by all similar documents over a 3-year window. Each discipline makes an equal contribution to the metric, which eliminates differences in researcher citation behaviour.

5 | ANALYSIS OF RESEARCH TRENDS

In this section, the co-occurrence analysis of keywords is performed. Analysis of keyword co-occurrence is the bibliometric method used to map the research field. The process of creating keyword networks and clustering keywords is aimed at identifying the main research fields in the area of blockchain and environmental sustainability. The analysis starts considering the keywords of all the considered papers. When working with keywords, the occurrence attribute indicates the number of documents in which a keyword occurs. The minimum number of occurrences of a keyword that was considered was equal to 5. In addition, all keywords were considered (i.e., author keywords and index keywords). The papers comprising the research sample provide 2978 keywords. The most cited expression is blockchain (289), followed by sustainable development (51) and technology development (47).

In Figure 8, the size of nodes manifests the frequency of keyword occurrence, while lines show relationships among keywords (co-occurrence). The map shows, in other words, the combinations of keywords that appear most frequently on the macrotheme 'blockchain'. For example, terms A and B may be said to 'co-occur' if they both appear in a particular article. Another article may contain terms B and C. Linking A to B and B to C creates a co-occurrence network of these three terms. For each of the keywords, the total strength of the co-occurrence links with other keywords was calculated. The keyword with the greatest total link strength is selected. Figure 8 displays the mainstream research keywords in 'blockchain' and 'sustainability' and their co-occurrence

TABLE 6 Top 10 of most relevant contributions

#	Authors	Title	Year	Citations	FWCI	Journal
1	Saberi, S., Kouhizadeh, M., Sarkis, J., Shen, L.	Blockchain technology and its relationships to sustainable supply chain management	2019	288	56.96	International Journal of Production Research
2	Vranken, H.	Sustainability of bitcoin and blockchains	2017	96	16.07	Current Opinion in Environmental Sustainability
3	Khaqqi, K. N., Sikorski, J. J., Hadinoto, K., Kraft, M.	Incorporating seller/buyer reputation-based system in blockchain-enabled emission trading application	2018	108	11.95	Applied Energy
4	Sharma, P. K., Park, J. H.	Blockchain based hybrid network architecture for the smart city	2018	102	12.49	Future Generation Computer Systems
5	Hughes, L., Dwivedi, Y. K., Misra, S. K., Rana, N. P., Raghavan, V., Akellad, V.	Blockchain research, practice and policy: Applications, benefits, limitations, emerging research themes and research agenda	2019	108	34.58	International Journal of Information Management
6	Huang, X., Xu, C., Wang, P., Liu, H.	LNSC: A security model for electric vehicle and charging pile management based on blockchain ecosystem	2018	87	13.22	IEEE Access
7	Xu, C., Wang, K., Guo, M.	Intelligent resource management in blockchain-based cloud datacenters	2017	78	8.73	IEEE Cloud Computing
8	Lin, Y.-P., Petway, J. R., Anthony, J., Mukhtar, H., Liao, S.-W., Chou, C.-F., Ho, Y.-F.	Blockchain: The evolutionary next step for ICT e-agriculture	2017	82	6.94	Environments—MDPI
9	Kouhizadeh, M., Sarkis, J.	Blockchain practices, potentials, and perspectives in greening supply chains	2018	80	9.28	Sustainability (Switzerland)
10	Cocco, L., Pinna, A., Marchesi, M.	Banking on blockchain: Costs savings thanks to the blockchain technology	2017	65	5.93	Future Internet

relationships. Thus, a holistic intellectual landscape of blockchain research was obtained. Co-occurrences are used to understand the underlying patterns of the document set under study. In the network visualization, we identified a modular network characterized by seven distinct but interrelated clusters. A cluster is a set of keywords that have co-occurrence relationships. A keyword may belong to only one cluster. Conventionally, in VOSviewer, clusters are labelled using cluster numbers and colours. Each point in the item density visualization has a colour that indicates the density of items at that point. By default, colours range from blue (lowest score) to yellow (highest score). To provide a clearer characterization of each cluster in addition to the colour (assigned by default by VOS), we assigned a label. We chose the name of the label with the aim of characterizing the items contained in each cluster. We labelled these clusters based on their main research theme: *Supply Chain Management* (Cluster 1 'Red') contains 26 items focusing on practice and supply chain management (e.g., business, cost reduction and sustainability), hence the name of Supply Chain Management. Similarly, the other clusters were labelled *Technological Infrastructure* (Cluster 2 'Green'), *Energy* (Cluster 3 'Blue'), *Smart Money* (Cluster 4 'Yellow'), *Climate Change* (Cluster 5 'Magenta'), *Technology Integration* (Cluster 6 'Light Blue') and *Emergent Trend* (Cluster 7 'Orange').

In particular, Table 7 summarizes significant items that are the result of the co-occurrence analysis shown in Figure 7. In addition, to explore the relationship between items and authors, we performed an in-depth analysis of each paper, as shown in Table 7.

The salient results and issues of inquiry in each cluster are summarized in the following sections.

5.1 | Cluster 1 'Red': Supply Chain Management

Cluster 1 is in a central position in the bibliographic coupling network in Figure 8. Research included in this cluster is focused above all on the macrotheme of the *supply chain*. This issue is analysed globally (see Table 7 for details). Blockchain-based supply chains are fundamentally changing the way companies do business, offering decentralized end-to-end processes via public blockchain. Saberi et al. (2019), for instance, examine the advantages of blockchain

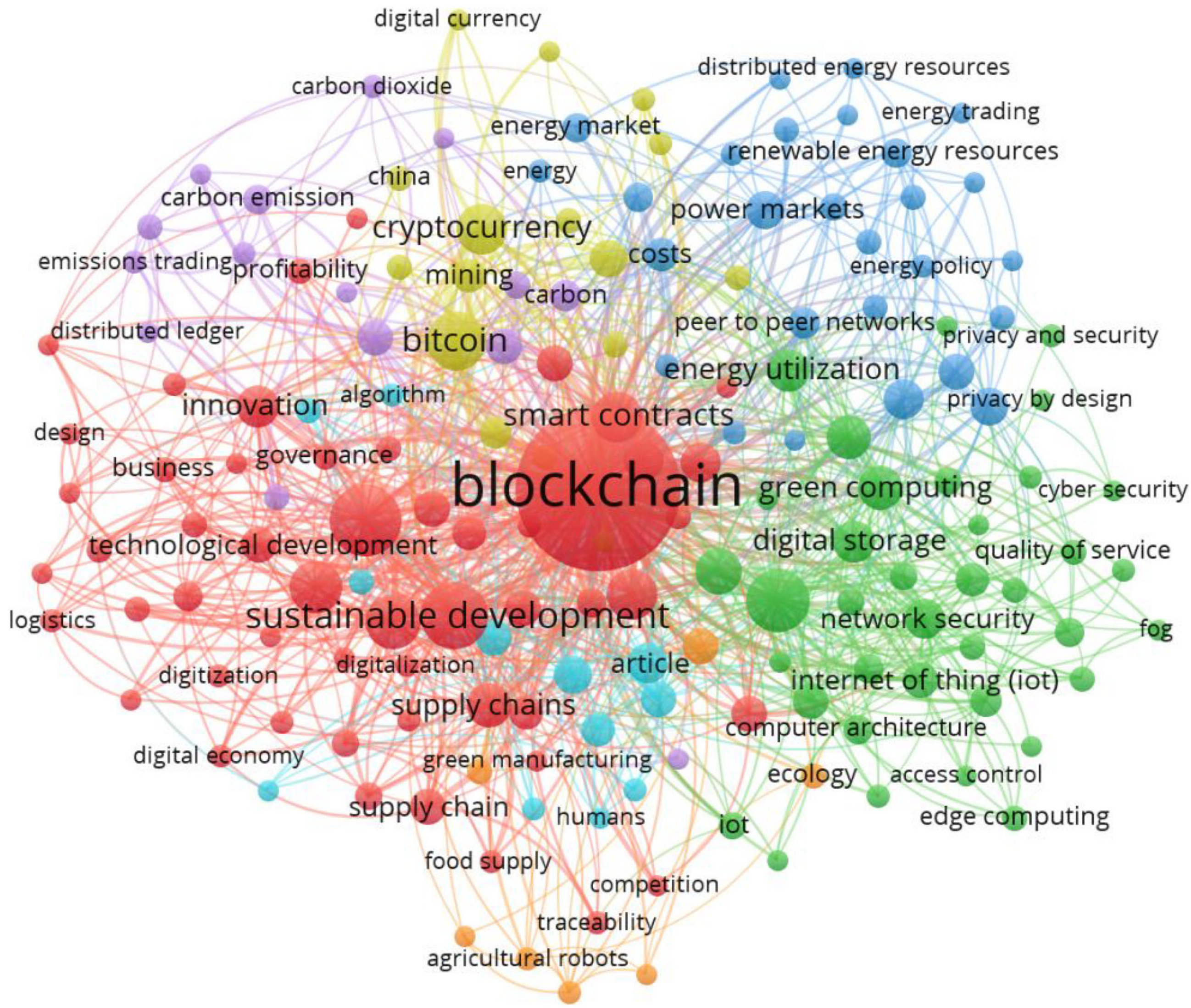

FIGURE 8 Co-occurrence analysis (VOSviewer) [Colour figure can be viewed at wileyonlinelibrary.com]

technology as a distributed digital ledger technology that ensures transparency, traceability and security. Moreover, in this field of research, Hastig and Sodhi (2020) work on supply chain traceability systems for blockchain applications in the cobalt mining and pharmaceutical industries. In addition, the potential of blockchain in supply chain management and smart contracts has been critically examined by several authors (Choi & Luo, 2019; Cole et al., 2019; Kamble et al., 2020; Kouhizadeh & Sarkis, 2018). In this context, it is also relevant to analyse the economic benefit of this technology for supply chain management or in specific areas, such as the food supply chain, as detailed by different authors (Astill et al., 2019; Duan et al., 2020; Howson, 2020; Wong et al., 2020). Regarding the supply chain, Kittipanya-Ngam and Tan (2020) specify that digitalization allows food supply chains to be highly connected, efficient and responsive to customer needs and regulation requirements. However, there are also adoption barriers during the integration process of blockchain, as clarified and summarized by some authors (Kouhizadeh et al., 2021; Öztürk & Yildizbaşi, 2020) in their very recent study. Data safety decentralization, accessibility, data management and quality are key factors that lead to the integration of blockchain with the supply chain, resulting in achieving sustainability, as explained by Yadav and Singh (2020). Furthermore, blockchain promotes cooperation between the main players in the strategic sector (e.g., the aviation industry) to reduce fragmentation, inefficiency and uncoordinated operations (Di Vaio & Varriale, 2020). In addition, it increases the speed of payment and the reliability and transparency of data transfer outlined by Lahkani et al. (2020). As discussed by Manupati et al. (2020), the distributed ledger-based blockchain approach (integrated with a mixed integer nonlinear programming model) can be used to monitor supply chain performance and to optimize both emission levels and operational costs. Some potentials and advantages of blockchain are related to smart contracts that facilitate the implementation of collaborative logistics structures in the environment of transnational and multimodal supply chains, as argued by Philipp et al. (2019). A supply chain

TABLE 7 Clusters, items and authors (VOSviewer and author's elaboration)

Clusters	Colour	No. of items	Cluster label	Details items (VOSviewer)	Main authors (author's own elaboration)
Cluster 1	Red	26	Supply Chain Management	Business, commerce, circular economy, competitiveness, knowledge, costs reduction, economic analysis, decentralization, design, digital economy, digitalization, distributed ledger, governance, green manufacturing, Industry 4.0, information management, innovation, logistics, sustainability, traceability transparency, stakeholder, empirical analysis, integrated approach and smart contracts	Saberi et al. (2019) Hastig and Sodhi (2020) Kouhizadeh and Sarkis (2018) Cole et al. (2019) Kamble et al. (2020) Choi and Luo (2019) Wong et al. (2020) Astill et al. (2019) Howson (2020) Duan et al. (2020) Kittipanya-Ngam and Tan (2020) Kouhizadeh et al. (2021) Öztürk and Yildizbaşi (2020) Yadav and Singh (2020) Di Vaio and Varriale (2020) Lahkani et al. (2020) Manupati et al. (2020) Philipp et al. (2019) Fan et al. (2018)
Cluster 2	Green	23	Technological Infrastructure	Access control, architecture, authentification, cloud computing, cyber security, digital storage, data privacy, access control, consensus, edge computing, distributed networks, fog computing, green computing, privacy, security, scalability, smart city, cryptography, future research directions, security of data and quality of service	Alonso et al. (2020) Rane and Thakker (2019) Rahman et al. (2019) Lu (2018) Ahad et al. (2020) Sharma et al. (2020) Ferrag et al. (2020) Singh et al. (2020)
Cluster 3	Blue	14	Energy	Alternative energy, economic effect, social effects, energy market, energy policy, energy resources, energy trading, energy management, electric vehicles, microgrids, smart grid, renewable energy, energy conservation and prosumer	Wu and Tran (2018) Park et al. (2018) Sharma (2019) Thakur and Breslin (2018) Rottondi and Verticale (2017)
Cluster 4	Yellow	7	Smart Money	Coins, cryptocurrency, digital currency, electronic money, learning systems, optimization and Ethereum	Vranken (2017) Truby (2018) Zimmer (2017) Li et al. (2019) Goodkind et al. (2020) Kim and Chung (2018) Fadeyi et al. (2020)
Cluster 5	Magenta	7	Climate Change	Emission, climate change, emission control, emission trading, environmental sustainability, Paris Agreement and carbon dioxide	Mata Dona (2019) Franke et al. (2020) Khaqqi et al. (2018) Fu et al. (2018) Yuan et al. (2019)
Cluster 6	Light Blue	5	Technologies Integration	Algorithm, artificial intelligence, big data, emerging technologies and integration	Limba et al. (2020) Kumari et al. (2020) Jo et al. (2019) Kim and Huh (2020)
Cluster 7	Orange	4	Emergent Trend	Agricultural robots, data analytics, engineering education and ecology	Lin et al. (2017) Klerkx and Rose (2020) Ciruela-Lorenzo et al. (2020)

represents, in other words, a complex network of distant and separate entities that exchange goods, payments and data across a dynamic and ever-changing landscape (Fan et al., 2018). In this context, blockchain, which is configured as a decentralized network with distributed and transparent data structures, allows a disparate group of network actors to exchange data relatively easily and from anywhere in the world in near real time, reducing efficiencies and enhancing supply chain environmental sustainability.

5.2 | Cluster 2 'Green': Technological Infrastructure

Cluster 2 examines technological infrastructure and IoT strategies in the context of blockchain. The IoT market, in terms of value, is set to grow at a composite average annual rate (CAGR) of 32.4% (Alonso et al., 2020). Blockchains will represent the reference infrastructure for the operation of this 'web of intelligent objects' (Rane & Thakker, 2019). Through the blockchain integrated with the IoT, it will also be possible to track billions of connected devices and coordinate millions of them with each other, allowing significant savings for IoT industry producers (Rahman et al., 2019). A decentralized approach will make it possible to eliminate the presence of single points of failure, creating a more resilient ecosystem for devices and at the same time guaranteeing consumer privacy, which is made more secure thanks to the cryptographic algorithms used by the blockchain. Lu (2018) affirms that the integration of blockchain and IoT can help companies promote and monitor the effect of their behaviour on SDGs. Among the possible applications, smart cities are also the focal point of this thimble transformation with sensors and actuators embedded in smart devices, as explained by Ahad et al. (2020). There are also many IoT applications in blockchain that offer opportunities and challenges, including the field of green IoT-based agriculture (Ferrag et al., 2020; Sharma et al., 2020). Another interesting application is a deep learning-based IoT-oriented infrastructure for a secure smart city where blockchain provides a distributed environment at the communication phase of the cyber-physical system (CPS) developed by Singh et al. (2020).

5.3 | Cluster 3 'Blue': Energy

Cluster 3 displays a significant interest in technical advantages of the blockchain to the energy sector (Wu & Tran, 2018). The production, sale and transmission of electricity is a decidedly complex activity that involves very different operators and affects millions of consumers/users. Thus, this sector is well suited to the blockchain. In fact, it can allow an automatic and traceable way to bring together small producers and consumers of energy, with obvious benefits for both parties. For instance, Park et al. (2018) provide a power trade system to promote a sustainable electrical energy-transaction ecosystem between prosumers and consumers of smart homes using a blockchain-based peer-to-peer (P2P) approach. Sharma (2019) proposed an energy-transaction model for the blockchain-enabled Internet of Vehicles. Thakur and Breslin (2018) propose a solution based on blockchain to reduce the waiting time for a microgrid to trade energy with other microgrids. Other authors have proposed research on smart grids. For example, Rottondi and Verticale (2017) present a smart metering architecture in which users have access to their own high-frequency data and can use them as the input data to a multiparty secure protocol.

5.4 | Cluster 4 'Yellow': Smart Money

Cluster 4 mostly includes research on Bitcoin, cryptocurrency and digital currency. One of the most discussed themes is how much energy is consumed to ensure the security of the blockchain (Truby, 2018; Vranken, 2017; Zimmer, 2017). For instance, Li et al. (2019) provide an estimation of global electricity consumption of *Monero* mining activity. In a recent study, Goodkind et al. (2020) estimated the per coin economic damages of air pollution emissions and associated human mortality and climate impacts of Bitcoin, Ethereum, Litecoin and Monero in the United States and China. Another topic covered in this cluster is social networks that use cryptocurrencies to pay users who publish blogs. In 2018, Kim and Chung (2018) proposed a process for building a desirable model of a token economy based on the case of Steemit suggesting some design process of token economy models. Finally, Fadeyi et al. (2020) contextualize energy use in smart cities through mining virtual currencies to predict whether smart cities can truly be sustainable if cryptomining is sustained. It is clear that utility-type cryptographic tokens issued via smart contracts on the Ethereum blockchain or similar blockchains can now be used to incentivize individuals and companies to act sustainably by incorporating gamification mechanisms into the model.

5.5 | Cluster 5 'Magenta': Climate Change

Cluster 5 mostly includes research on climate change aspects. An interesting point of view is offered by Mata Dona (2019), who explores the use of blockchain as an innovative junction tool between international investment law and climate change law with the potential to increase foreign investment in climate change mitigation and adaptation. Franke et al. (2020) examine the benefits of applying blockchain technology according to the Paris Agreement carbon market mechanism by investigating two platforms, Ethereum and Hyperledger Fabric. Several solutions have been proposed to improve the emission trading scheme (ETS). An example is the use of blockchain to address ETS management proposed by Khaqqi et al. (2018) or by Fu et al. (2018) for the fashion apparel manufacturing industry. A Hyperledger-based ETS aiming to provide credible trading services for polluters was developed by Yuan et al. (2019). A different application is formulated by Thess et al. (2020). In their research, a novel approach, global carbon charge (GCS), which mimics a carbon tax, was discussed. The model requires that all companies store these materials immediately after mining for a given period of time. If compulsory storage is coupled to blockchain-based smart contracts and a mandatory (expensive) mining of cryptocurrency, GCS can be operated without governmental protectionism, corruption and fraud. Smart contracts and token incentive mechanisms have great potential in terms of environmental and social sustainability.

5.6 | Cluster 6 'Light Blue': Technology Integration

Cluster 6 displays a significant interest in the integration of some specific technologies from the perspective of blockchain. For instance, Limba et al. (2020) analyse factors of big data implementation in the sector of cryptocurrency and in the sector of municipal waste management. The theme is very relevant, as it is well known that today, many aspects of our life can be translated into big data. The sharing of data could be lost, corrupted, outdated or acquired by unauthorized third parties. Blockchain represents a solution to these critical issues, allowing the possibility of sharing and making data accessible to all the subjects participating in the chain without the possibility of error and corruption (Jo et al., 2019; Kumari et al., 2020). However, the production of big data, the analysis of much data and insertion into the blockchain are all operations that require increasing processing capacity (and consequent energy consumption). In a different study proposed by Kim and Huh (2020), a blockchain-based carbon emission rights verification system was developed to learn proven data further by using governance system analysis, big data and artificial intelligence in mobile cloud environments. It should also be noted that currently, the implementation of smart contracts is mostly based on traditional algorithms. However, in the future, it is expected that some of these implementations can reach higher levels of complexity up to real adaptive algorithms, typical of the classical methods of artificial intelligence. In these cases, it will be natural to use the entire knowledge base contained on the blockchain.

5.7 | Cluster 7 'Orange': Emergent Trend

The last cluster is the least number of applications. However, it is characterized by applications in emerging fields. With these premises, we note that in today's agri-food market, the difficulty in certifying the origin and quality of an agricultural product is a problem for the consumer as much as it is for farms and large-scale distribution, as already highlighted by Lin et al. (2017). Blockchain can help not only to guarantee the entire traceability of the production chain and processing of agricultural products in total transparency but also to make a more sustainable use of natural resources (such as water) and to reduce the emissions associated with the production and transportation of food products (Ciruela-Lorenzo et al., 2020; Klerkx & Rose, 2020). Thus, it is clear that digital innovation in food traceability undoubtedly represents a great opportunity for the sector.

6 | RELATIONSHIPS BETWEEN BLOCKCHAIN AND ENVIRONMENTAL SDGs

It is clear that blockchain is a disruptive technology that is spreading increasingly and that is starting to come out of the niche of the financial and insurance world to penetrate the manufacturing, agro-food and public administration sectors. Consequently, the impact of blockchain on the environment will be an important issue for future years. Accordingly, in this section, we try to emphasize this latter aspect linking blockchain to environmental SDGs. The first step is to identify direct or indirect references to environmentall-related SDGs to selected papers (see Appendix B). The results are presented in the Table 8.

In particular, Tables 8 shows that:

- *Considered issue* means the number of papers that have considered the specific SDG in the text; the percentage (%) indicates the number of the papers on the total sample on the sample total. *SDG 7* (Affordable and Clean Energy) is the goal most considered in the papers, followed by *SDG 12* (many papers analyse the use of blockchain for the sustainable development of the supply chain), *SDG 13* (Climate Action) and *SDG 11* (blockchain for smart cities and sharing economy).

TABLE 8 Relationships between blockchain and SDGs (author's elaboration)

	SDG 6 Clean Water and Sanitation	SDG 7 Affordable and Clean Energy	SDG 9 Industry Innovation and Infrastructure	SDG 11 Sustainable Cities and Communities	SDG 12 Responsible Consumption and Production	SDG 13 Climate Action	SDG 14 Life Below Water	SDG 15 Forests, Desertification and Biodiversity
Issue	19	135	54	60	93	77	6	12
%	974	69.23	27.69	30.77	47.69	39.49	3.08	6.15
+ 12	Effect	18	97	51	56	84	13	6
%	100	72	94	93	90	17	100	100
− 0	Effect	0	44	3	5	9	65	0
%	0	33	6	8	10	84	0	0
Main 3	topic	8	78	25	36	61	36	2
%	42	58	46	60	66	47	33	25

- *Positive/negative effect* means the number of papers that identify a positive relationship between the specific SDG and blockchain; the percentage (%) is the number of papers on the total sample. It is important to note that the percentage is not the absolute number because there are some papers that consider a bidirectional effect of the blockchain on the specific goal. Regarding the effects, our

TABLE 9 Relationship matrix between SDGs and clusters (author's elaboration)

SDGs		Cluster 1 Red	Cluster 2 Green	Cluster 3 Blue	Cluster 4 Yellow	Cluster 5 Magenta	Cluster 6 Light Blue	Cluster 7 Orange
6	Clean Water and Sanitation		x	x				
7	Affordable and Clean Energy			x				
9	Industry Innovation and Infrastructure				x		x	
11	Sustainable Cities and Communities		x					
12	Responsible Consumption and Production	x						
13	Climate Action					x		
14	Life Below Water							
15	Forests, Desertification and Biodiversity							x

TABLE 10 Challenges/potentials of blockchain to environmental-related SDG achievement (author's elaboration)

#SDGs	Description	Goal	Potentials	Challenges
6 CLEAN WATER AND SANITATION	Clean Water and Sanitation	Ensure access to water and sanitation for all	Support peer-to-peer trading of water rights	Develop a new form of shared value creation in which a network of actors agrees on a specific objective to ensure equal use of the resource 'water'
7 AFFORDABLE AND CLEAN ENERGY	Affordable and Clean Energy	Ensure access to affordable, reliable, sustainable and modern energy for all	Develop smart contracts for renewable energy producers and consumers	Develop blockchain systems based on alternative energy or reduced energy consumption
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Industry Innovation and Infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	Develop smart contract for transport and logistics	Resources required can represent a barrier to the effectively implementation Define a set of incentives to sustain blockchain adoption
11 SUSTAINABLE CITIES AND COMMUNITIES	Sustainable Cities and Communities	Make cities inclusive, safe, resilient and sustainable	Creating more liveable cities implementing platforms to monitor energy consumption, waste and so on	Define a blockchain model that integrate different technologies
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Responsible Consumption and Production	Ensure sustainable consumption and production patterns	Enables tracking and tracing of supply chains and natural resource usage	Require for a complementary assets to be effective
13 CLIMATE ACTION	Climate Action	Take urgent action to combat climate change and its impacts	Develop platforms for monitoring and exchange greenhouse gas emissions quotes	Develop blockchain systems based on alternative energy
14 LIFE BELOW WATER	Life Below Water	Conserve and sustainably use the oceans, seas and marine Resources	Implementation mechanisms to monitor water pollution and preserve marine resources (e.g., fishering biological stop)	Develop models for reducing waste and assessing the environmental impact thanks to complete information transparency on collective sustainability behaviours
15 LIFE ON LAND	Forests, Desertification and Biodiversity	Sustainably manage forests, combat desertification and halt and reverse land degradation and halt biodiversity loss	Offer small cash payments in exchange for conserving nature	Optimize energy processes, enabling communication between smart devices and making transactions with partners and suppliers more efficient

analysis shows that a large part of the authors focus on the positive effect of blockchain for all the SDGs. A limited number of the papers investigate the negative effects that are mainly concentrated on the *SDG 7* (Affordable and Clean Energy) because the authors usually underline the negative effect linked to the higher energy consumption of the servers used for the transactions. Moreover, the authors also underline the negative effect on *SDG 13* (Climate Action) with a specific concern about the increasing level of CO_2 emissions derived by extensive blockchain mining.

- *The main topic* is the number of papers in which the relationship between the technology and the specific SDG (although not specifically named as such) represents the main topic of the paper. The percentage value shows the number of the papers on the total sample. The strong focus is on *SDG 12*, for which the role of blockchain on the supply chain often represents the main topic of the paper, more than the impact of energy and on energy on technology, despite all showing this relationship.

Therefore, we developed a relationship matrix between SDGs and clusters (see Table 9). The matrix is the results of the analysis of all 195 papers and contents with respect to the SDGs. Table 9 summarizes the main contribution of each SDG related to the clusters. In other words, the analysis of the 195 papers highlighted that the objectives of the SDGs are directly linked to the identified clusters. For example, SDG 12 ‘Responsible Consumption and Production’ seems mainly considered from the study that analyses the blockchain applied to the supply chain because this latter technology helps the development of a more sustainable supply chain. SDG 7, ‘Affordable and Clean Energy’, finds some correspondence in Cluster 3 (Energy) because blockchain can support energy transactions, especially regarding alternative energy. Moreover, SDG 13 (Climate Action) is linked to the study of blockchain as an instrument to evaluate and exchange carbon emission quotes (Cluster 5). SDG 15 (Forests, Desertification and Biodiversity) is mainly linked to Cluster 7 (Emergent), which includes studies that analyse the new application of the blockchain in new industry as agriculture. Studies on the technological infrastructure of blockchain (Cluster 2) consider the potential of this technology in enhancing environmental sustainability in terms of Clean Water and Sanitation (SDG 6) and Sustainable Cities (SDG 11).

Starting from the positive and negative effects that blockchain has on environmental SDGs, it is possible to identify the main elements on which to intervene to support the use of blockchain for the realization of a more sustainable world. At this point, the question is *What are the challenges for the coming future? What are Blockchain technology potentials*? The main strength of the blockchain is that it is a ‘transversal’ technology applicable in very different fields. Thus it is clear how it can offer multiple opportunities to save the environment acting on different SDGs. On the other side, the use of blockchain is linked to many challenges that companies have to face for this technology adoption. Table 10 summarizes some potentials and challenges of blockchain for each SDG.

7 | CONCLUSIONS

Blockchain technology is often considered one of the most remarkable innovations in the 21st century, and its application can generate a remarkable change in all economic activities.

In a period where technological innovation must go hand to hand with environmental sustainability, it is important to understand the relationships between blockchain and the natural environment. Accordingly, our paper aims to investigate in detail the complex relationship between blockchain adoption and environmental sustainability. Through a systematic literature review and a content analysis of the selected papers, our work has emphasized the conflictual relationship between blockchain and environmental SDGs. In particular, our study reveals that authors have destined increasing attention to blockchain technologies and that the number of papers that link these technologies to the environment has increased in the last 2 years. Co-occurrence analysis shows that authors have addressed this topic for different points of view, for example, considering the role of blockchain in supporting the realization of a sustainable supply chain, analysing the role of smart contracts and their use for removable energy industry, considering the role of blockchain for carbon tax, analysing the opportunities offered by cryptocurrency as a way to reward sustainable behaviour and considering the chance offered by this technology to increase the environmental sustainability in particular industries. Our study shows that the application of blockchain technology offers many opportunities to create a more sustainable world, in line with SDGs.

Analysing the link between blockchain and SDGs, it is clear that the most debated relationship regards the effect of blockchain on Affordable and Clean Energy (SDG 7) because blockchain can support the development of alternative energy, operationalizing the use of smart contracts to exchange energy quotes, especially for renewable energy (Park et al., 2018), or, for example, to recharge electric vehicles (Sharma et al., 2020). The use of blockchain can also have a positive impact on Climate Action (SDG 13), giving the opportunity to map and exchange carbon emissions (Franke et al., 2020) or using blockchain and cryptocurrency to create a system of incentives to reward low pollution behaviours (Thess et al., 2020). Moreover, scholars affirm that blockchain can be also used to enable tracking and tracing the supply chain (Responsible Consumption and Production, SDG 12) (Saberi et al., 2019), to create more liveable cities implementing platforms to monitor energy consumption, waste and so on (Sustainable Cities and Communities, SDG 11) (Ahad et al.. 2020) and to create mechanisms to reward sustainable behaviours and penalize actions that damage the environment such as polluting water (SDG 14) or reducing biodiversity (SGD 15) (França et al., 2019).

Other studies, especially those that analyse blockchain algorithms, highlight the negative effects of blockchain. The massive use of these technologies can generate increasing energy consumption and consequent CO_2 emissions acting negatively on other SDGs (Climate Action, SDG 13); moreover, traditional blockchain technologies require the construction of large buildings to host the server, negatively impacting the landscape (SDG 11) (Yadav & Singh, 2020).

In other words, blockchain is destined to change the economy in the immediate future, matching the necessity to have a very high level of transparency and economic efficiency with the goal of reaching a more sustainable world. On the other hand, our paper offers a warning about the potential negative effect of blockchain for the environment, suggesting users balancing the positive and negative aspects.

Therefore, our research offers interesting theoretical implications because it gives a whole exploration of the effect of blockchain on the natural environment; moreover, the linkage with SDGs highlights which aspects are already addressed and which aspects need to be more explored. Moreover, our paper gives the measure of the complexity of the relationship between blockchain and environmental sustainability because existing studies consider only particular topics (such as supply chains and smart cities) or analyse environmental issues as a part of a large sustainability problem without putting enough emphasis on environmental aspects. Last but not least, the existing studies analyse only specific SDGs or only positive effects without giving a whole view of the phenomenon. From a practical point of view, our paper provides useful insights to both managers and policy makers, providing a guideline to understand the possible applications and potential benefits of this technology. In particular, our paper can help managers develop an open mind regarding the implementation of new technologies; indeed, sometimes, the adoption of new technologies is motivated only by economic reasons. Our results show managers that the implementation of new high-tech solutions such as blockchains can also be motivated by the necessity to improve firms' environmental sustainability. On the other hand, they suggest that managers should be aware of the possible environmental challenges that can be derived from the adoption of blockchain solutions.

Regarding policy makers, our paper provides a useful framework to define initiatives that can promote environmental sustainability in coherence with the United Action's policy. Indeed, the 17 SDGs defined by the United Nations are part of a broader programme of action to which all countries are called to join. Recognizing the role of blockchain technologies to boost many sides of environmental sustainability gives policy makers the suggestion to promote the creation of suitable technology infrastructure that supports blockchain execution and that can facilitate the implementation and diffusion of this technology at both public and private levels to enhance environmental sustainability. Despite its interesting implications, our study also presents several limitations that can be addressed in future works. As a bibliometric analysis of a relatively new topic, a deeper understanding of the connection between blockchain and environmental sustainability requires a longer longitudinal observation. Second, to provide a greater validity of the theoretical positive and negative effects of blockchain on environmental sustainability, our framework needs to be empirically tested.

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APPENDIX A: KEYWORD RESEARCH

Environmental-related SDGs	Explanation	Keywords
SDG 6 Clean Water and Sanitation	Ensure availability and sustainable management of water and sanitation for all	"Clean water" "drinking water" "water quality" "water scarcity" "wastewater" "desalination" "sanitation" "open defecation"
SDG 7 Affordable and Clean Energy	Ensure access to affordable, reliable, sustainable and modern energy for all	"clean energy" "sustainable energy" "renewable energy" "energy efficiency" "smart grid" "fossil-fuel" "access to power"
SDG 9 Industry Innovation and Infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	"sustainable industr*" "green innovation" "resource efficiency" "sustainable innovation" "clean innovation" "resilient infrastructure" "SME" "Upgrad* infrastructure"
SDG 11 Sustainable Cities and Communities	Make cities and human settlements inclusive, safe, resilient and sustainable	"sustainable transport*" "sustainable cit*" "smart cit*" "sustainable urbanization" "sustainable building" "smart building" "air quality" "smart mobility" "sustainable mobility"
SDG 12 Responsible Consumption and Production	Ensure sustainable consumption and production patterns	"sustainable product*" "sustainable consum*" "food waste" "sustainable procurement" "sustainable life cycle" "recycling" "sustainable tourism" "responsible product*" "responsible consum*" "responsible tourism" "green procurement" "waste management"
SDG 13 Climate Action	Take urgent action to combat climate change and its impacts	"climate change" "natural disaster" "global warming" "gas emission" "pollution" "greenhouse gas" "climate emergency" "global temperature" " CO_2" "natural hazard" "clime mitigation" "clime adaptation" "carbon dioxide"
SDG 14 Life Below Water	Conserve and sustainably use the oceans, seas and marine resources for sustainable development	"ocean" "marine biodiversity" "marine resources" "ocean acidification" "marine pollution" "marine ecosystem" "coastal ecosystem" "marine debris" "overfishing" "fishing practice" "fish stocks"

APPENDIX B: RELATIONSHIP BETWEEN SDGs AND SELECTED PAPERS

SDGs	Papers
SDG 6 Clean Water and Sanitation	1, 9, 12, 28, 30, 39, 49, 66, 67, 89, 146, 190, 197, 242, 243, 275, 295, 300, 322
SDG 7 Affordable and Clean Energy	1, 5, 6, 9, 10, 11, 14, 15, 17, 19, 20, 21, 24, 25, 28, 30, 31, 32, 34, 35, 39, 40, 41, 45, 47, 49, 50, 52, 54, 55, 57, 60, 66, 67, 69, 71, 74, 79, 82, 83, 84, 86, 89, 90, 91, 92, 96, 98, 99, 101, 102, 103, 104, 107, 108, 110, 112, 113, 114, 115, 120, 126, 137, 140, 146, 149, 150, 157, 168, 171, 172, 174, 175, 177, 179, 181, 184, 199, 204, 217, 221, 222, 224, 228, 235, 238, 239, 242, 243, 248, 249, 251, 255, 261, 262, 263, 266, 269, 270, 271, 272, 273, 274, 275, 276, 284, 286, 287, 288, 290, 291, 292, 293, 294, 295, 296, 300, 306, 308, 312, 313, 314, 316, 317, 318, 320, 321, 322, 327, 331, 333, 337, 342, 343, 344
SDG 9 Industry Innovation and Infrastructure	1, 6, 9, 14, 15, 17, 30, 32, 44, 46, 54, 63, 103, 104, 107, 109, 112, 116, 117, 123, 127, 140, 144, 147, 151, 158, 160, 167, 209, 214, 217, 231, 255, 269, 270, 273, 291, 292, 293, 295, 308, 314, 316, 318, 320, 321, 322, 328, 329, 333, 340, 342, 344, 345
SDG 11 Sustainable Cities and Communities	7, 9, 10, 17, 20, 26, 34, 41, 44, 46, 49, 98, 101, 103, 104, 108, 111, 112, 117, 120, 126, 140, 147, 149, 159, 165, 167, 171, 174, 209, 224, 230, 243, 255, 269, 270, 273, 288, 292, 293, 296, 300, 308, 312, 313, 314, 316, 317, 321, 322, 326, 328, 329, 330, 331, 333, 340, 343, 344, 345
SDG 12 Responsible Consumption and Production	1, 6, 9, 10, 11, 12, 14, 15, 17, 19, 21, 24, 25, 28, 30, 39, 41, 46, 47, 49, 54, 57, 62, 64, 74, 78, 79, 83, 86, 89, 90, 92, 96, 97, 103, 107, 108, 109, 111, 112, 114, 116, 117, 120, 123, 140, 151, 158, 185, 190, 209, 214, 237, 242, 246, 259, 260, 263, 265, 266, 269, 272, 273, 274, 275, 287, 288, 290, 291, 294, 295, 298, 299, 300, 301, 308, 309, 312, 316, 318, 320, 321, 322, 324, 325, 326, 328, 329, 331, 341, 342, 343, 345
SDG 13 Climate Action	1, 6, 14, 15, 17, 19, 25, 30, 39, 41, 47, 49, 52, 54, 55, 67, 71, 76, 79, 84, 89, 91, 92, 95, 96, 98, 107, 108, 110, 112, 113, 114, 147, 168, 172, 181, 184, 185, 190, 228, 238, 239, 243, 248, 249, 250, 251, 259, 260, 262, 266, 269, 270, 272, 275, 284, 288, 291, 292, 293, 295, 300, 302, 306, 308, 314, 315, 317, 321, 322, 332, 333, 341, 342, 343, 344, 346
SDG 14 Life Below Water	67, 103, 242, 266, 342, 343
SDG 15 Forests, Desertification and Biodiversity	39, 157, 190, 214, 239, 242, 266, 291, 299, 308, 309, 342